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A STUDY OF THE DISPERSION CLIMATOLOGY OF THE PICKERING AREA

Report No 84-137-K

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ABSTRACT

A year-long preliminary experimental program was carried out in the Pickering NGS area to collect meteorological information which is important in determining dispersion and transport of air pollutants. Data were collected by acoustic sounders, net pyrradiometers, anemometers and thermocouples. These data were analyzed to give seasonal and diurnal frequencies of occurrence of wind velocity, atmospheric stability, inversions and the formation of thermal internal boundary layers. An advection model was developed to illustrate the applicability of data collected in this study in predicting the growth rate of the thermal internal boundary layer. The likely behaviour of an emitted plume was discussed in terms of the local meteorological conditions for two selected cases. It is concluded that continuous shoreline fumigation and trapping may occur over the Pickering area. However, looping and lofting may also be comparably important, especially for low-level releases. Numerical modelling and tracer experiments will be essential to gain further insight into microscale effects on the dispersion climatology of the Pickering area.

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To Mr. F.J. Kee
Director of Research

A STUDY OF THE DISPERSION CLIMATOLOGY OF THE PICKERING AREA

1.0 INTRODUCTION

1.1 Background

Ontario Hydro operates a power system throughout most of the inhabited areas of the Province. This system includes hydraulic, fossil-fuelled and nuclear power generating stations. Knowledge of the fate and consequences of emissions released to the atmosphere is required for the design, licensing and operation of the fossil-fuelled and nuclear generating stations. This information is usually acquired by conducting monitoring studies at the sites of interest and performing modelling studies of the physical and chemical processes undergone by the releases.

Until recently, most of the work has been concerned with the fossil-fuelled thermal generating stations. For example, extensive field studies have been carried out at the Nanticoke (Djurfors, 1974; McMillan, 1977; Portelli, 1982) and Lakeview (Edwards, 1982) areas. The operational usefulness of acoustic sounders was also explored in these studies (Kerman et al, 1982; McMillan and Lemyk, 1983). On the other hand, relatively few studies have been conducted at nuclear generating stations. Radioactive materials may be released into the atmosphere during routine normal operation of nuclear generating stations or as a result of an accident. The need to know the dispersion climatology at nuclear generating stations is vital, especially to assess the significance of chronic and acute emission releases.

Ontario Hydro has five nuclear generating stations currently in operation and under construction. They are Nuclear Power Demonstration (20 MW); Douglas Point (220 MW); Bruce A and B (6328 MW); Pickering A and B (4320 MW) and Darlington (3524 MW). Pickering was chosen as the study site because it is close by. This study is considered as the first of a series of studies dealing with field investigations around nuclear generating stations. If successful, further studies will then be carried out at other Ontario Hydro nuclear generating stations.

1.2 Objectives and Scope of the Present Study

The present study has three major objectives:

(1) to collect local meteorological information in the Pickering NGS area by a year-long experimental program initiated in February, 1982

(2) to identify the dispersion climatology affecting the behaviour of emissions released in the area

(3) to document the data needed to develop and validate physical and mathematical dispersion models.

These objectives were accomplished by a network of instrumentation situated in the Pickering NGS vicinity. The instrument package included two monostatic and one bistatic acoustic sounders, two net pyrradiometers, two anemometers and two thermocouples. Descriptions and locations of these instruments are given in Section 2.0.

The fate of air pollutants from the time they leave the source is governed by the thermal and mechanical structure of the atmosphere. Important meteorological variables are wind velocity, atmospheric stability and the height of the surface mixed layer. The seasonal and dirunal frequency distributions of these meteorological variables were analyzed based on the data collected in the present study. An advection model was developed to illustrate the applicability of the data collected in this study to predict the growth rate of the thermal internal boundary layer. Case studies were also discussed in terms of the local meteorological conditions. Results are presented in Sections 3.0 and 4.0 and concluding remarks are given in Section 5.0.

2.0 EXPERIMENTAL DESCRIPTION

2.1 Instrumentation

The instruments used in the present study include acoustic sounders, net pyrradiometers, anemometers and thermocouples.

2.1.1 Acoustic Sounders

Acoustic sounders are relatively new remote-sensing devices which use the scattering of sound waves from fluctuations in the atmosphere to detect atmospheric thermal and mechanical structures. The scattering of sound in the atmosphere is due to local variations in the sound propagation velocity which is a function of the temperature and velocity components of the air. The scattering cross-section σ may be given by

$$\sigma(\theta, f) = 0.055 \left(\frac{f}{C}\right)^{1/3} \cos^2\theta \left[\frac{C_V^2}{C^2} \cos^2\left(\frac{\theta}{2}\right) + 0.136 \frac{C_T^2}{T^2}\right] \left(\sin\frac{\theta}{2}\right)^{-11/3} \qquad (2\text{-}1)$$

where θ is the angle between transmitted and received beams, f is the frequency of the sound wave, C is the mean speed of sound, C_V^2 and C_T^2 are the structure parameters which are related to the mean square fluctuations in velocity and temperature, respectively, and T is the mean absolute temperature.

The acoustic sounder equation can be expressed as

$$P_r = P_t \, L \, S \, \frac{\ell}{2} \, \alpha \, G \, \frac{A}{R^2} \, \sigma \, (\theta, f) \qquad (2\text{-}2)$$

where P_r and P_t are the received and transmitted acoustic power, respectively, L is the atmospheric attenuation, S is the pulse stretching factor, ℓ is the pulse length, α is a dimensionless factor which accounts for the shape of the reflecting layer, G is the antenna gain factor, A is the area of the receiver antenna aperture and R is the distance from the receiver antenna to the reflecting layer. Thus, the structure of the atmosphere can be determined from the varying strength of the return sound signals according to Equations (2-1) and (2-2).

Two monostatic and one bistatic acoustic sounder systems were used in this study. In the case of the monostatic acoustic sounder system, the antenna serves both as a transmitter and a receiver for the 1600 Hz sound pulse signal. Thus, $\theta = 180$ and Equation (2-1) becomes

$$\sigma = 0.00748 \, \left(\frac{f}{C}\right)^{1/3} \, \frac{C_T^2}{T^2} \qquad (2\text{-}3)$$

In other words, the scattering cross-section of the monostatic acoustic sounder depends only on temperature inhomogeneities, C_T^2.

Contrarily, a bistatic acoustic sounder system consists of the basic monostatic components and an additional transmitting antenna which emits a fan-beamed acoustic signal located approximately 150 m away. Accordingly, the bistatic acoustic sounder records signals backscattered due to both temperature and velocity inhomogeneities. Figure 1 gives a schematic of these two systems. More comprehensive descriptions may be found in Kerry (1981).

The acoustic sounder systems used in the present study are the Model 300C manufactured by AeroVironment Inc, USA. The specifications for the Model 300C are listed in Table I.

2.1.2 Net Pyrradiometer

The net pyrradiometer is based on the principle that net radiation is the difference between the total incoming and outgoing radiation fluxes at all wavelengths. In general, the incoming radiation is the shortwave solar radiation and the outgoing radiation is the longwave radiation reflected from the earth's surface. The difference between these two radiations may be determined from the energy flux imbalance between the upper and lower faces of a sensing element.

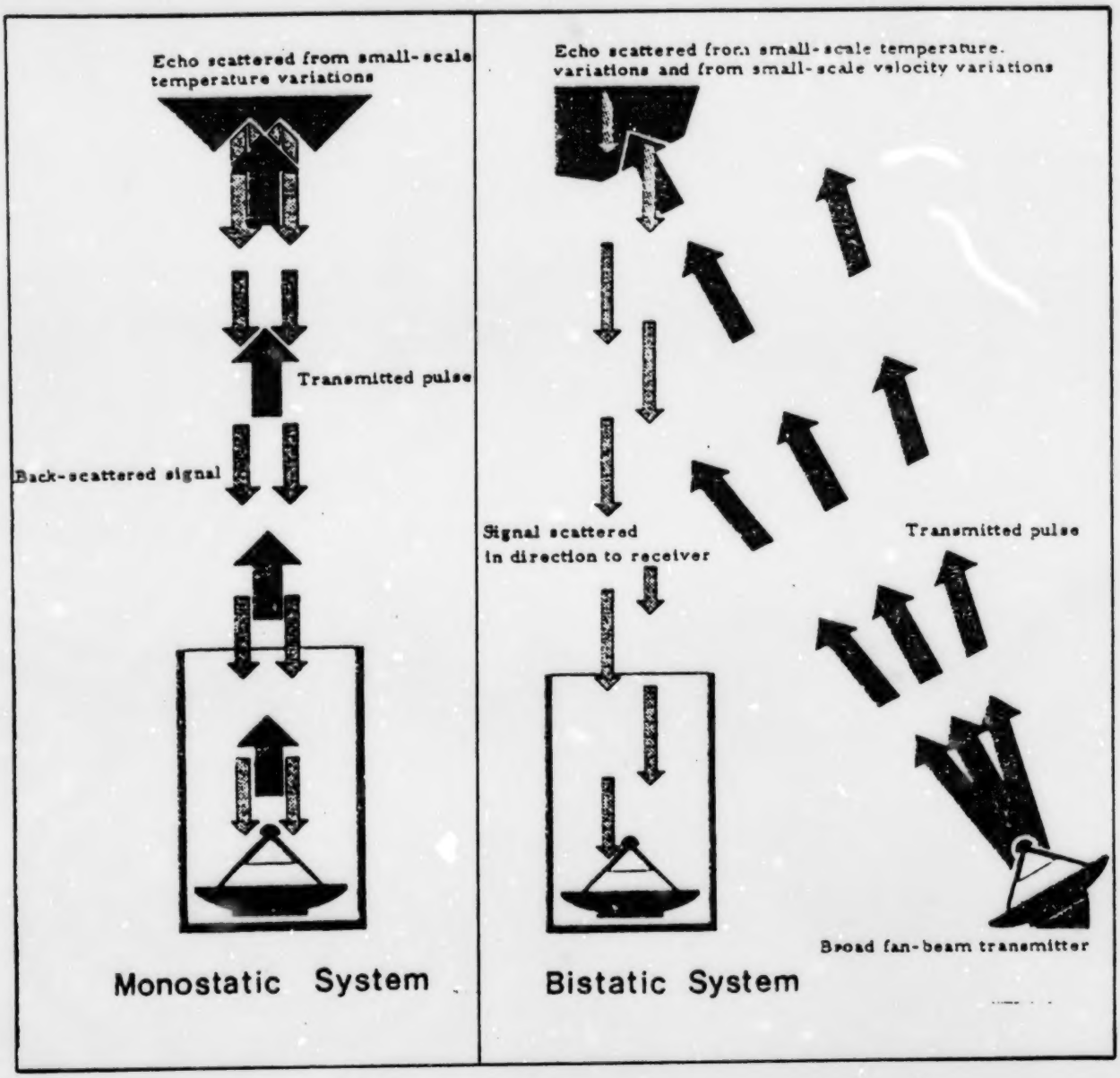

Echo scattered from small-scale temperature variations
Transmitted pulse
Back-scattered signal
Monostatic System
Echo scattered from small-scale temperature variations and from small-scale velocity variations
Signal scattered in direction to receiver
Transmitted pulse
Broad fan-beam transmitter
Bistatic System

FIGURE 1

SCHEMATIC OF MONOSTATIC AND BISTATIC ACOUSTIC SOUNDER SYSTEMS

TABLE I

SPECIFICATIONS FOR THE ACOUSTIC SOUNDER SYSTEM MODEL 300C

Transmitter:	Frequency - 1600 Hz
	Pulse Width - 50, 100, 200 ms
	Output Power - 100 watts
	Output Impedance - 8 ohms
	Pulse Repetition Rate - 1 per 9 sec (500 m scale)
	- 1 per 18 sec (1000 m scale)
	Monostatic/Bistatic Switching - Automatic alternating
Receiver:	Gain - 10^8
	Gain Compensation - proportional to time from transmit
	Bandwidth - 20, 40, 80 Hz
	Range - 500 m, 1000 m full scale
	- 20 m minimum
	Resolution - 10 m
Display:	Type - Time-Height-Intensity (THI)
	Technique - electrical engraving of conductive paper
	Chart Size - 6" (15.2 cm)W x 72' (22 m)L
	Chart Speed - 1.2" (3.05 cm) per hour
	Chart Duration - 28 days
Size:	17.5" (44.5 cm)L x 17.5" (44.5 cm)W x 8.5" (21.5 cm)H
Weight:	45 lbs (20.5 kg)
Power Requirements:	115 VAC, 60 Hz, 50 W average, 250 W peak
Operating Temp. Range:	5 °C to 40°C

The net pyrradiometers used in the present study are the CSIRO Funk Model manufactured by Middleton Instruments, Australia. The sensing element of the system is a blackened plate across which there is a thermopile of 250 junctions with sensitivity of about 40 mV Cal^{-1} cm^{-2} min^{-1} and a time constant of about 40 s. This sensing element is covered by a thin polyethylene dome for protection and balance of the convective heat exchange between the upper and lower domes. In the field, the plate is aligned parallel to the ground surface to ensure the measurement of incoming radiation from the upper face and outgoing radiation from the lower face of the sensing element.

2.1.3 Other Instrumentation

Two anemometers, one Climet and one Bendix-Freiz, and two Rustrak thermocouples were used to measure wind velocities and surface temperatures respectively. Except for the Bendix-Freiz anemometer, all these instruments were operated and maintained by the Design and Development Division of Ontario Hydro.

2.2 Site Locations

Figure 2 displays the geographical location of Pickering NGS. It is located on the north shore of Lake Ontario, about 35 km east of metropolitan Toronto. The area surrounding Pickering NGS is relatively flat with open farm areas to the north. The terrain height increases gradually from about 75 m above mean sea level (MSL) at the shoreline to slightly over 300 m above MSL at about 25 km inland from the lake. The Duffin Creek and the Rouge River run approximately north-south across the area.

In order to obtain representative three-dimensional structure of the atmosphere over the Pickering area, the previously-mentioned instruments were positioned at three sites in a triangular configuration. These three sites are designated as the Lakeshore, Zoo and Greenwood Sites. The locations in UTM coordinates and types of instruments used at each site are listed in Table II and displayed in Figure 3.

The Lakeshore site was located at the Duffin Creek Water Treatment Plant next to Pickering NGS. A bistatic acoustic sounder system and a net pyrradiometer were installed at this site. The Climet anemometer was mounted at the 10-m level and a Rustrak thermocouple was placed at the 1-m level of a meteorological tower within the Pickering NGS property. Note that the separation of the acoustic sounder from the other instruments was necessary due to the relatively high ambient noise level at the power plant.

The Zoo site was located at about 9 km west of Pickering NGS and 6 km inland from the closest shoreline. The instruments used at this site were a monostatic acoustic sounder, a net pyrradiometer and a Rustrak thermocouple.

FIGURE 2

THE LOCATION OF PICKERING NGS

TABLE II

THE LOCATIONS AND TYPES OF FIELD INSTRUMENTATION USED IN THE 1982 PICKERING STUDY

Site	Lakeshore	Zoo	Greenwood
UTM coordinates	4852500 mN 656000 mE	4854100 mN 646000 mE	4862800 mN 654500 mE
Direction from Pickering NGS	85°	275°	355°
Distance from Pickering NGS	0.8 km	9.5 km	11.5 km
Type of Instrument	1) Monostatic/ Bistatic Acoustic Sounder 2) Net Pyrradiometer 3) Climet Anemometer 4) Rustrak Thermo-couple	1) Monostatic Acoustic Sounder 2) Net Pyrra-diometer 3) Rustrak Ther-mocouple	1) Monostatic Acoustic Sounder 2) Bendix-Freiz Ane-mometer

Lakeshore Site - Monostatic/Bistatic Sounder, Net Pyrradiometer

Lakeshore - Surface Temperature & Anemometer (10m)

× Zoo Site - Monostatic Sounder, Net Pyrradiometer & Surface Temperature

• Greenwood Site - Monostatic Sounder, Anemometer (13m)

FIGURE 3

THE LOCATIONS AND TYPES OF FIELD INSTRUMENTATION USED IN THE 1982 PICKERING STUDY

The Greenwood site was located about 10.5 km north of Pickering NGS. This site was equipped with a monostatic acoustic sounder and the Bendix-Freiz anemometer, mounted at the 13-m level of a portable telescopic tower.

2.3 Data Recovery Rate

The acoustic sounder data were recorded continuously since March, 1982. The capture rate of acoustic sounder data at each site for the one-year study period is given in Table III. As shown, the data capture rate was reasonably good.

TABLE III

ACOUSTIC SOUNDER DATA RECOVERY RATE (%)
(numbers in brackets denote days in operation)

	Lakeshore	Zoo	Greenwood
February, 1982	100 (3)	100 (3)	-
March, 1982	87 (27)	87 (27)	100 (17)
April, 1982	100 (3)	100 (3)	73 (22)
May, 1982	100 (31)	65 (20)	71 (22)
June, 1982	100 (30)	30 (9)	50 (15)
July, 1982	26 (16)	100 (31)	19 (6)
August, 1982	74 (18)	100 (31)	100 (31)
September, 1982	53 (15)	87 (26)	97 (29)
October, 1982	100 (31)	100 (31)	100 (31)
November, 1982	93 (28)	94 (29)	100 (30)
December, 1982	100 (31)	100 (31)	100 (31)
January, 1983	100 (31)	100 (31)	90 (18)
February, 1983	68 (19)	100 (28)	32 (25)

The net pyrradiometers were operated from April, 1982 to October, 1982. Within this period, there were 144 and 109 data days at the Lakeshore and Zoo sites, respectively. Both the acoustic sounder and net pyrradiometer data have been abstracted and reported separately by Lemyk (1983, a,b,c) and Wenglewick (1983), respectively.

Wind data at the Lakeshore site have been recorded continuously since September, 1972 by Design and Development Division. Data at the Greenwood site were collected from July, 1982 onward by Research Division. Surface temperature data were recorded starting in July, 1982. Neither the wind nor the surface temperature data were abstracted by the Atmospheric Research Section and thus, no data reports were issued for these two variables. In fact, Design and Development Division abstracted the raw data into usable format for our purposes. The analysis of the available data is discussed in the following sections.

3.0 RESULTS

3.1 Statistical Aspects

The principal meteorological variables that influence the dispersion and transport of air pollutants at the shoreline environment are wind velocity, atmospheric stability, height of the mixed layer and the formation of thermal internal boundary layers. This section describes the seasonal and diurnal distributions of the frequency of occurrence of these variables in the Pickering area found during the 1982 study period and based on the available observed data. Except for the winds, results are presented for onshore flow conditions only since this is of major interest to Ontario Hydro.

3.1.1 Wind Velocity

Figure 4 and Table IV show the seasonal distributions of surface winds at the Lakeshore site. The predominant winds at this site during the 1982 study period were from the east and from the southwest through the north-northwest. The predominant wind speeds were in a range between 10 and 20 km h^{-1}. The average wind speeds for the spring, summer, fall and winter were 15, 11, 13 and 17 km h^{-1}, respectively.

Studies at fossil-fuelled thermal generating stations indicate that most of the potential air pollution episodes in the shoreline environment occur during gradient or lake breeze onshore flow conditions. Onshore flow conditions in the Pickering area occur when the surface wind direction at the Lakeshore site is in the range of from 90° (east) to 225° (southwest). As shown in Table IV, approximately 35% of the winds were within this range during the spring, summer and fall months and 29% in the winter months. Further examination of the wind data at the Lakeshore site reveals that there were 140 days in which onshore flows were recorded for at least 6 hours during the 1982 study period, 38 days in spring, 30 days in summer, 39 days in fall and 33 days in winter. Most of these onshore flows were due to synoptic weather patterns, such as high pressure systems situated over the New England States. Some were the result of lake breezes. For the lake breeze cases, onshore flows occurred during the day time hours and the speeds of onshore flows were stronger than those of flows at other hours.

3.1.2 Atmospheric Stability

The seasonal distributions of the frequency of occurrence of stable, unstable and neutral atmospheric conditions at each of the three sites during onshore flow days were congregated according to acoustic sounder data. There are two primary types of acoustic echo features which commonly appear on the acoustic sounder facsimile charts: layer echoes and spike echoes. The layer echoes are associated with temperature inversions and thus, they indicate the presence of stably stratified layers in the atmosphere. On the other hand, the spike echoes are associated with convective activity and they indicate the presence of unstable layers in the atmosphere.

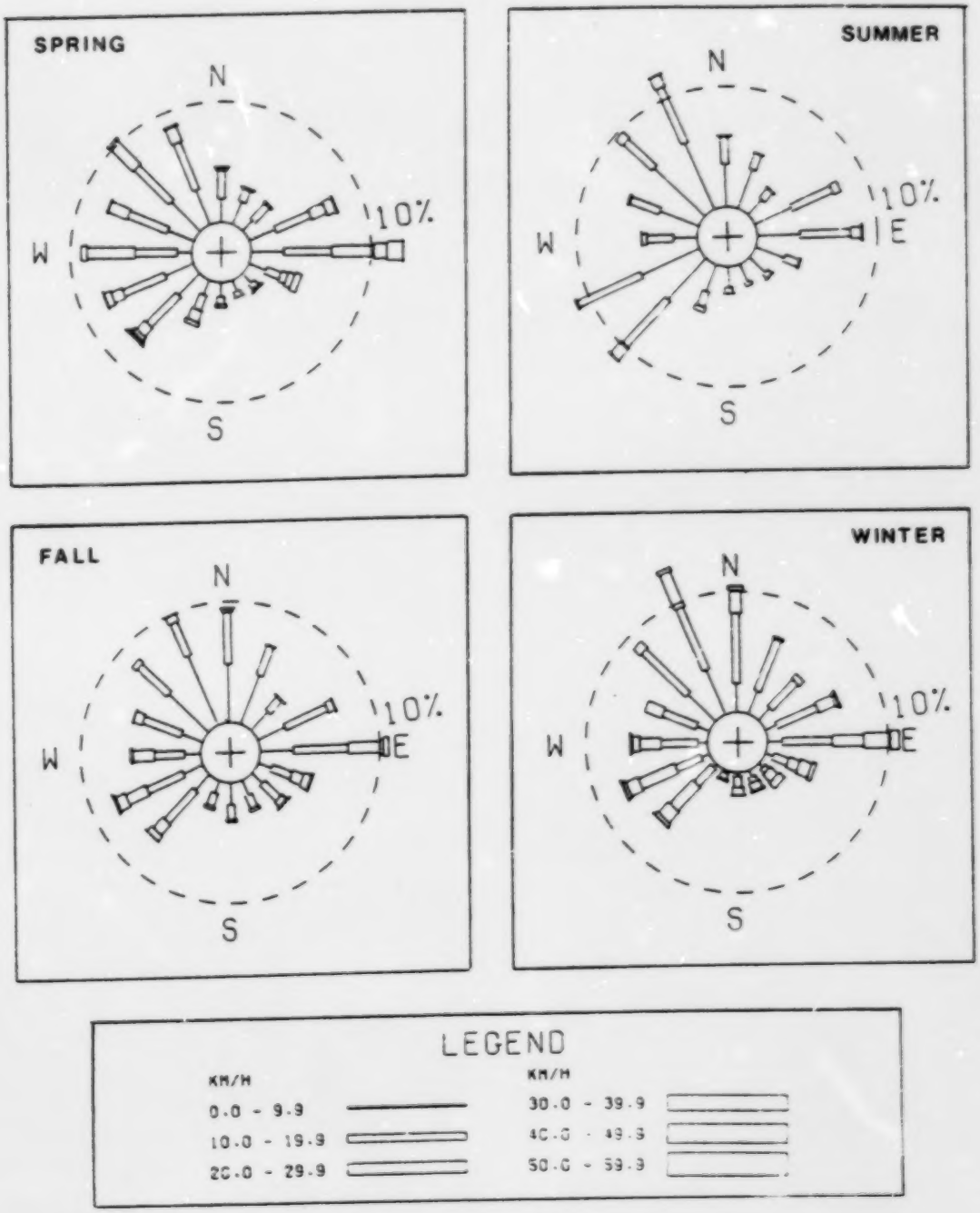


FIGURE 4

SEASONAL DISTRIBUTION OF SURFACE WINDS
AT THE PICKERING LAKESHORE SITE IN 1982

TABLE IV

PERCENTAGE FREQUENCIES OF SURFACE WIND SPEED AND DIRECTION AT THE PICKERING LAKESHORE SITE IN 1982

PERIOD FROM MAR 01/82 TO MAY 31/82

DIRECTION FROM	WIND SPEED RANGES IN KM/H										
	·0 - 9·9	10·0 -19·9	20·0 -29·9	30·0 -39·9	40·0 -49·9	50·0 -59·9	60·0 -69·9	70·0 -79·9	80·0 -89·9	>89·9	TOTAL %
N	1·95	2·31	·27	·05							4·58
NNE	2·00	1·04	·14	·05							3·22
NE	1·18	1·68	·18								3·04
ENE	2·31	3·17	1·32	·77	·14						7·71
E	2·72	3·99	3·54	1·09	1·32	·05					12·70
ESE	1·54	1·27	·59	·54	·59						4·54
SE	1·09	·50	·18	·09							1·86
SSE	1·00	·45	·09								1·54
S	1·22	·43	·27								2·13
SSW	1·32	1·32	1·00	·36							3·99
SW	2·49	3·45	·95	·32	·18	·18	·05				7·62
WSW	2·49	3·72	1·00	·59	·09						7·89
W	1·18	3·45	3·99	·50							9·12
WNW	2·31	3·49	1·72	·09							7·62
NW	3·40	4·04	2·81	·23							10·48
NNW	3·08	4·22	1·36	·18							8·84
CALM	3·13										3·13
TOTAL %	34·42	38·73	19·41	4·85	2·31	·23	·05	·00	·00	·00	100·00

PERIOD FROM JUN 01/82 TO AUG 31/82

DIRECTION FROM	WIND SPEED RANGES IN KM/H										
	·0 - 9·9	10·0 -19·9	20·0 -29·9	30·0 -39·9	40·0 -49·9	50·0 -59·9	60·0 -69·9	70·0 -79·9	80·0 -89·9	>89·9	TOTAL %
N	3·55	2·24	·09	·05							5·94
NNE	3·46	1·36	·05								4·86
NE	1·68	1·03	·09								2·81
ENE	3·32	3·69	·65								7·67
E	3·55	4·21	·84	·14	·05						8·79
ESE	2·57	1·26	·14								3·97
SE	1·82	·47	·09								2·38
SSE	1·64	·33									1·96
S	1·73	·51	·05								2·29
SSW	2·38	1·31	·42								4·11
SW	4·68	5·14	1·36	·09							11·27
WSW	5·28	5·75	·19								11·22
W	1·96	2·20	·42	·05							4·63
WNW	3·46	2·57	·19								6·22
NW	5·80	3·18	·75								9·72
NNW	5·98	5·05	1·03	·09							12·16
CALM											·00
TOTAL %	52·88	40·30	6·36	·42	·05	·00	·00	·00	·00	·00	100·00

TABLE IV (cont'd)

PERIOD FROM SEP 01/82 TO NOV 30/82

DIRECTION FROM	WIND SPEED RANGES IN KM/H										
	·0 - 9·9	10·0 -19·9	20·0 -29·9	30·0 -39·9	40·0 -49·9	50·0 -59·9	60·0 -69·9	70·0 -79·9	80·0 -89·9	>89·9	TOTAL %
N	4·83	4·30	·29	·05							9·47
NNE	4·30	2·56	·05								6·91
NE	2·08	1·40	·05	·05							3·58
ENE	2·51	3·82	·58	·10							7·01
E	2·80	4·54	2·61	·34	·43						10·73
ESE	1·21	1·79	·97	·63	·19						4·78
SE	1·21	1·88	·48	·14	·05						3·77
SSE	1·35	1·11	·29								2·75
S	1·84	1·21	·24								3·29
SSW	1·06	1·11	·29								2·46
SW	1·74	3·48	1·16	·53	·05						6·96
WSW	1·79	3·24	1·84	·87	·19	·05					7·97
W	1·35	2·45	1·79	·24							5·85
WNW	1·88	3·33	·77	·10							6·09
NW	4·59	3·33	·48								8·41
NNW	6·28	3·00	·63	·05							9·96
CALM											·00
TOTAL %	40·84	42·58	12·52	3·09	·92	·05	·00	·00	·00	·00	100·00

PERIOD FROM DEC 01/82 TO FEB 28/83

DIRECTION FROM	WIND SPEED RANGES IN KM/H										
	·0 - 9·9	10·0 -19·9	20·0 -29·9	30·0 -39·9	40·0 -49·9	50·0 -59·9	60·0 -69·9	70·0 -79·9	80·0 -89·9	>89·9	TOTAL %
N	2·36	5·83	1·94	·32							10·46
NNE	2·04	4·54	·23								6·81
NE	1·39	3·01	·56								4·95
ENE	1·02	3·66	1·48	·23	·19						6·57
E	1·20	4·17	2·64	2·18	·74						10·93
ESE	·69	1·30	·93	1·02	·37						4·31
SE	·46	·46	·83	·65							2·41
SSE	·60	·46	·65	·19							1·90
S	·32	·93	·65	·05							1·94
SSW	·23	·51	·19								·93
SW	·32	1·99	2·69	1·20	·32	·09					6·62
WSW	·69	2·27	3·24	1·06	·28	·14					7·69
W	·74	3·06	1·76	·60	·14	·09					6·39
WNW	1·11	2·96	1·48								5·56
NW	3·15	5·14	·74								9·03
NNW	4·03	5·56	3·15	·32							13·06
CALM	·46										·46
TOTAL %	20·83	45·83	23·15	7·82	2·04	·32	·00	·00	·00	·00	100·00

The absence of acoustic echoes usually indicates neutral or very slightly stable atmospheres. Results based on these classifications are presented in Table V.

Generally, air over a body of water is more stable than air over a land surface. This effect is consistent with the trends shown in this table. At the Lakeshore site, there were 2079 hours of stable conditions, but only 239 hours of unstable and 282 hours of neutral conditions throughout the 1982 study period. The corresponding occurrences (number of hours) of these three stability conditions at the Zoo site and Greenwood site were 1602, 636 and 393 and 1388, 625 and 188, respectively. Note that the acoustic sounder data recovery rate is different for each site and season (see Table III). Accordingly, results shown in Table V cover those cases for which data were available simultaneously at all three sites.

Table VI gives the seasonal percentage frequency of occurrence of each of the three atmospheric stability conditions at each of the three sites. It may be seen that most of the stable and unstable conditions at the Lakeshore site occurred in spring and fall while most of the neutral conditions occurred during summer and winter. At the Zoo site, the highest frequencies of stable conditions occurred in fall and winter while those of unstable and neutral conditions occurred in summer and fall. A slightly different pattern was observed at the Greenwood site where most of the stable and neutral conditions occurred in fall and winter and most of the unstable conditions occurred in summer and fall.

Different atmospheric stability conditions lead to different pollutant plume characteristics. These are discussed here, first for the classical case of elevated releases and then for the case of releases from CANDU plants. In a stable atmosphere, the shape of the plume may remain essentially unchanged to a long distance downwind from the source because of very weak vertical transport. This phenomenon is called "fanning." The ground-level concentration of pollutants is primarily determined by the diffusion of the pollutant itself if the release is at a very low altitude ($\sim$50 m) or due to sudden changes in terrain features in the downwind direction, which can cause the plume to intersect the ground. In these cases, instantaneous ground-level concentrations may be very high since the plume is diluted slowly.

In an unstable atmosphere, the plume can be brought to ground by relatively large eddies in the air in the so-called "looping" plume behaviour. However, looping usually gives high instantaneous concentrations at quite short distances downwind from the source. The ground-level concentrations will then decrease very rapidly over longer distances. The rate of looping is also dependent upon the terrain features and the wind speed.

A phenomenon called "coning" may occur in a neutral atmosphere. Under this condition, the vertical and lateral dispersions of the pollutant plume are about equal. The maximum ground-level concentration would occur at a greater distance downwind from the source than is the case with looping.

TABLE V

SEASONAL OCCURRENCE OF ATMOSPHERIC STABILITY IN HOURS IN 1982 AS DETERMINED BY ACOUSTIC SOUNDER

STABLE CONDITIONS

	LAKESHORE SITE	ZOO SITE	GREENWOOD SITE
SPRING	682	223	234
SUMMER	499	307	295
FALL	587	519	530
WINTER	311	553	329
Total	2079	1602	1388

UNSTABLE CONDITIONS

	LAKESHORE SITE	ZOO SITE	GREENWOOD SITE
SPRING	102	108	117
SUMMER	31	226	201
FALL	99	198	247
WINTER	7	104	60
Total	239	636	625

NEUTRAL CONDITIONS

	LAKESHORE SITE	ZOO SITE	GREENWOOD SITE
SPRING	52	62	15
SUMMER	90	119	28
FALL	36	125	69
WINTER	104	87	76
Total	282	393	188

TABLE VI

SEASONAL OCCURRENCE OF ATMOSPHERIC STABILITY IN % IN 1982 AS DETERMINED BY ACOUSTIC SOUNDERS

	STABLE CONDITIONS		
	LAKESHORE SITE	ZOO SITE	GREENWOOD SITE
SPRING	26.2	8.5	10.6
SUMMER	19.2	11.7	13.4
Fall	22.6	19.7	24.1
WINTER	12.0	21.1	15.0
Total	80.0	61.0	63.1

	UNSTABLE CONDITIONS		
	LAKESHORE SITE	ZOO SITE	GREENWOOD SITE
SPRING	3.9	4.1	5.3
SUMMER	1.2	8.6	9.1
FALL	3.8	7.5	11.2
WINTER	0.3	3.9	2.7
Total	9.2	24.1	28.3

	NEUTRAL CONDITIONS		
	LAKESHORE SITE	ZOO SITE	GREENWOOD SITE
SPRING	2.0	2.3	0.7
SUMMER	3.4	4.5	1.3
FALL	1.4	4.8	3.1
WINTER	4.0	3.3	3.5
Total	10.8	14.9	8.6

Other emission behaviours can occur under various complex atmospheric stabilities. For example, lofting occurs with stable air below, unstable or neutral air aloft. The stable air below would prevent pollutants from reaching the ground and thus, there is apparently no high ground-level concentrations.

Fumigation is the reverse situation to that of lofting, with unstable air below and stable or neutral air aloft. This condition can give very high ground-level concentration of pollutants over a very short period of time. Further discussion of these two situations will be given in later sections.

Based on Table VI and the plume characteristics, it may be estimated that for onshore flow conditions, a release from Pickering NGS has an 80% probability of initially entering into a stable atmosphere. As it travels inland to either the Zoo or the Greenwood areas, the probability that the atmosphere will still remain stable decreases to about 60%. Instead, there is a 24 to 28% probability that the air containing the release would become unstable there. In other words, fanning may be expected to occur initially at the Lakeshore area and looping at some distance inland from the shore.

Note that the above discussion of plume behaviour applies to general situations. In practical problems the plume behaviour may be very complex. The reactor building of Pickering NGS for example, is shaped like a vertical cylinder topped by a hemispherical dome. These reactor buildings are 47-m high. If a plume is released on the roof of the reactor building, the plume may be drawn into an area on the leeward side of the building by the so-called "building wake effect."

In light wind conditions, the plume may rise outside the wake boundary by buoyancy and may spread horizontally over an increasing area. When the wind is moderately high, the wake effect could cause the release to reach the ground surface and thus produce a high ground-level concentration very close to the building. Beyond the wake boundary, the plume would have characteristics similar to that of a puff and continuous release from an area source.

3.1.3 Inversions

An inversion is a layer of air in the atmosphere through which the temperature increases with altitude (or remains constant). Inversions play an important role in dispersion climatology because inversion layers are very stable thermodynamically and thus, tend to prevent mixing with air above and/or below.

The base and top of an inversion layer can be easily determined from temperature profiles. Figure 5 shows some examples as given by Holzworth (1974). There are two general types of inversions, the surface-based inversion and the elevated inversion. A surface-based inversion can restrict vertical mixing and thus, reduce the potential of having high ground-level concentrations of pollutants from elevated releases. On the other hand, an elevated inversion may trap pollutants in a stagnant layer of air between the inversion and the ground and may lead to increased concentrations of pollutant at ground level.

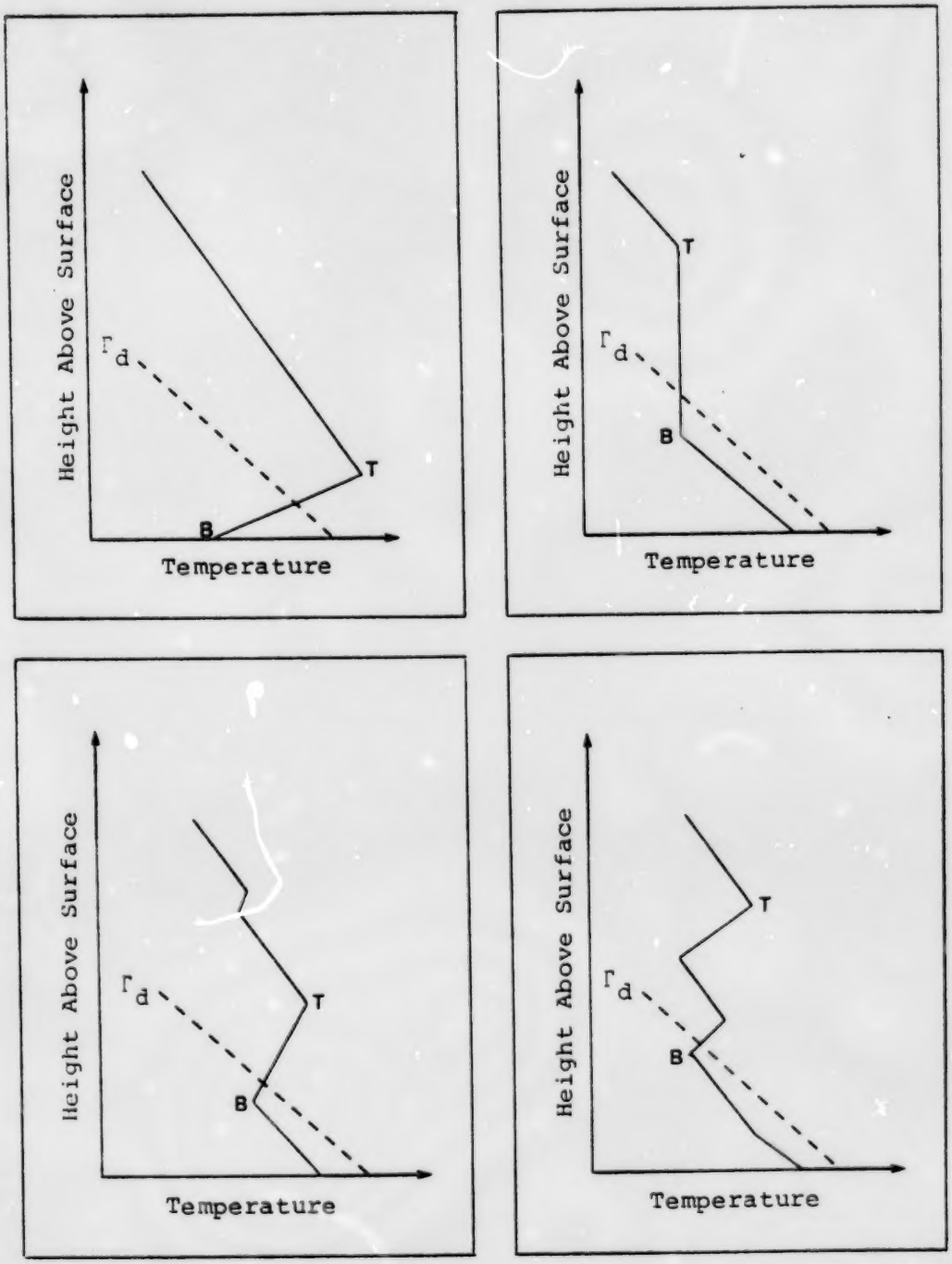


FIGURE 5

OBJECTIVE SCHEME FOR SPECIFYING BASE (B) AND TOP (T) OF INVERSIONS FOR VARIOUS TEMPERATURE PROFILE CONFIGURATIONS. Γ_d IS DRY ADIABATIC LAPSE RATE

Tables VII and VIII list the seasonal frequencies of occurrence, in percentage, of surface-based and elevated inversions for the three sites during onshore flow days in the 1982 study period, as determined from the acoustic sounder data.

The highest frequencies of occurrence of surface-based inversions were observed in spring and fall at the Lakeshore site, fall and winter at the Zoo site and summer and fall at the Greenwood site. The diurnal distributions of the occurrences are quite similar at all sites. The highest frequency was observed in the morning hours, while the lowest frequency was observed during late afternoon hours.

Table IX shows the average depths of the surface-based inversions observed during onshore flow days in this study. It can be noted that the maximum depth of the surface-based inversions at the Lakeshore site occurred in the morning hours. The depths then decreased as the day progressed to a minimum value in the late afternoon. Thereafter, the depths increased again. At the inland sites, the depths of surface-based inversions started to increase from the early morning to a peak at about noon time and to decrease thereafter. The rate of decrease was much larger at the inland sites than at the Lakeshore site. The depths increased again at night. It may also be noted that the maximum depth of the surface-based inversions was observed in winter months at all three sites, whereas the lowest depths occurred in the summer months.

The highest frequencies of occurrence of elevated inversions were observed in the fall months and during the day time for all sites. There were very few cases at night and in the morning hours. The diurnal distributions of the occurrence are more pronounced at the inland sites than at the lakeshore site. Tables X and XI display the average height of the base of elevated inversions and their average thicknesses during onshore flow days in this study. The highest bases occurred in the winter months for all sites with the maximum being observed at the Zoo site. Generally, the bases of elevated inversions rose in the morning hours and descended in the afternoon hours. This diurnal pattern is more apparent at the inland sites than at the Lakeshore site. The thicknesses of the elevated inversions are in general smaller than those of the surface-based inversions. The diurnal variations of the thickness were rather uniform with slightly thicker layers at night. Again, the maximum thicknesses were observed in the winter months. This may be due to subsidence of air from above, the so-called subsidence inversion, since the land surface is quite cold in the winter time.

3.1.4 Thermal Internal Boundary Layers

A boundary layer which develops inside another boundary layer is called an internal boundary layer. Causes for the development of an internal boundary layer are usually a change in surface conditions such as a change in terrain roughness or a change of surface temperature. The latter case is often referred to as the thermal internal boundary layer (TIBL).

TABLE VII

SEASONAL FREQUENCY OF OCCURRENCE (%) OF SURFACE-BASED INVERSIONS IN 1982

LAKESHORE SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING	36	36	36	34	31	29	29	29	33	35	35	36	35	35	35	33	31	33	31	29	28	29	31	27
SUMMER	22	23	26	27	30	33	31	30	31	34	36	37	33	28	28	23	28	25	22	16	19	19	19	19
FALL	35	36	35	32	36	40	40	40	36	35	36	36	32	34	35	35	31	30	28	31	36	36	38	35
WINTER	15	15	15	15	14	15	61	14	16	16	14	21	12	12	11	9	9	9	9	8	11	9	7	7

ZOO SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING	18	18	18	18	17	18	18	17	19	18	19	18	16	13	14	13	14	12	12	12	16	16	16	14
SUMMER	25	25	25	25	28	28	27	29	28	24	24	23	21	20	20	20	17	14	10	15	15	17	20	18
FALL	36	36	36	35	36	35	35	35	36	36	36	35	35	33	31	28	21	21	24	27	28	29	30	30
WINTER	29	29	28	31	30	30	30	30	32	31	29	29	29	27	26	28	26	21	24	24	24	24	26	24

GREENWOOD SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING	23	23	23	21	21	21	21	21	20	23	23	25	25	25	25	25	25	20	21	23	23	20	18	18
SUMMER	42	42	42	42	40	40	31	36	40	33	38	40	36	36	33	33	33	29	19	27	27	29	29	29
FALL	38	38	39	38	39	39	38	36	39	40	37	37	33	34	31	28	29	27	31	31	32	32	31	31
WINTER	27	27	27	27	27	26	26	23	23	22	23	20	19	19	17	16	14	12	11	12	14	14	14	14

TABLE VIII

SEASONAL FREQUENCY OF OCCURRENCE (%) OF ELEVATED INVERSIONS IN 1982

LAKESHORE SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING		1		1	2	2	2	2	3	3	2	5	3	5	2	2	1	2	1	1	1	1	1	
SUMMER	2	3	3	3	3	5	6	5	6	5	8	6	3	2			2		2	3	3	2	2	2
FALL	1	1	1	3	4	3	7	4	16	11	7	8	7	4	3	3	1	3	5	9	7	7	4	3
WINTER		1	1	2	2	2	2	2	2	2	2	4	1	1	1	2	2	1	1	2	4	4	2	2

ZOO SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING									7	8	5	4	4	4	5	5	5	4	3	1	1	1	1	1
SUMMER		1	1	1			1	14	14	11	7	4	3	3	3	4	4	4	1	1	1	1	1	1
FALL	1	2	5	5	6	7	7	9	19	22	24	20	15	14	15	15	14	5	8	6	5	4	2	1
WINTER	1	2	3	4	6	6	7	4	2	8	7	8	4	7	7	8	9	4	4	4	4	3	3	4

GREENWOOD SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING	2	2	2	3	3	2	2	7	10	8	5	7	7	7	7	7	8	7	2				2	2
SUMMER							6	13	21	13	13	12	12	8	8	6	8	10		2		2	2	
FALL	3	7	8	7	6	4	9	12	20	28	27	23	18	19	17	17	11	9	9	9	9	8	4	3
WINTER	5	5	5	7	5	4	5	5	7	8	9	8	7	8	8	7	4	3				2	2	3

TABLE IX

AVERAGE DEPTH (m) OF SURFACE-BASED INVERSIONS IN 1982

LAKESHORE SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING	200	200	190	190	210	230	210	220	200	190	180	160	150	140	140	140	120	150	160	170	180	190	190	200
SUMMER	210	210	220	230	200	180	200	200	180	190	180	180	130	120	130	140	130	100	110	140	140	150	190	180
FALL	250	240	330	270	270	270	270	260	230	250	240	230	190	190	180	180	180	180	170	200	200	230	260	250
WINTER	320	340	360	390	380	390	380	430	370	360	350	330	320	340	350	330	320	340	350	310	300	300	340	340

ZOO SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING	210	230	250	290	280	280	280	230	270	310	310	350	300	350	250	230	190	200	230	200	200	210	200	230
SUMMER	170	170	180	190	190	210	190	190	170	200	250	290	330	320	300	270	220	190	130	120	130	140	160	170
FALL	240	250	260	260	260	260	170	260	230	250	270	310	350	370	340	300	320	170	210	200	250	250	280	260
WINTER	350	360	360	350	370	360	360	340	320	310	330	340	380	350	350	300	270	320	370	390	410	430	410	400

GREENWOOD SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING	270	290	260	250	230	250	240	210	230	280	310	340	360	340	340	300	250	210	220	250	250	230	250	240
SUMMER	210	220	230	200	220	240	240	190	260	330	370	380	380	380	380	320	240	200	260	240	230	250	220	220
FALL	290	280	280	290	310	310	300	280	300	250	350	400	410	400	350	260	260	280	270	170	300	310	280	310
WINTER	420	410	420	400	390	400	410	480	440	450	460	580	630	650	660	590	590	530	710	670	580	500	500	510

TABLE X

AVERAGE HEIGHT OF THE BASE (m) OF ELEVATED INVERSIONS IN 1982

LAKESHORE SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING		380		140	230	260	140	140	120	110	130	210	260	210	180	200	240	240	200	700	600	600	480	
SUMMER	180	250	300	280	270	300	190	180	250	180	220	190	160	120			140		380	200	270	350	340	300
FALL	160	200	460	490	430	230	260	250	150	250	230	220	190	470	590	560	420	280	280	270	230	350	250	320
WINTER		560	540	480	460	480	550	510	510	450	370	410	220	240	220	210	260	380	480	630	500	470	390	370

ZOO SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING									110	150	210	200	210	230	210	190	160	140	450	740	580	600	400	520
SUMMER		360	360	370			80	110	210	230	250	290	180	150	150	200	140	130	270	280	220	230	230	200
FALL	60	210	130	150	140	160	180	150	140	120	300	350	350	320	280	230	160	140	180	120	150	200	420	130
WINTER	650	790	610	680	620	630	630	600	330	260	250	310	300	310	300	290	270	220	290	320	400	400	410	510

GREENWOOD SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING	230	220	180	310	260	400	350	210	220	250	230	310	200	230	250	200	180	130	180				140	160
SUMMER							100	150	210	260	250	330	280	240	330	220	210	150		140		100	240	
FALL	290	230	300	270	330	300	250	220	300	210	300	390	400	380	320	250	220	280	290	250	320	250	390	470
WINTER	320	450	540	360	400	380	310	290	260	230	360	420	420	510	590	520	340	340				220	140	460

TABLE XI

AVERAGE DEPTH (m) OF ELEVATED INVERSIONS IN 1982

LAKESHORE SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING		150		130	130	100	230	230	210	150	120	100	130	120	140	90	60	110	110	80	100	200		
SUMMER	80	60	50	60	110	120	170	180	140	80	140	110	100	100			100		140	210	100	140	200	230
FALL	80	100	240	190	190	180	200	170	150	150	150	130	150	100	110	140	180	130	170	130	120	140	170	180
WINTER		140	120	110	130	130	140	120	140	110	160	120	320	300	290	250	180	160	160	170	140	210	230	180

ZOO SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING									180	170	90	120	120	100	100	110	130	150	180	40	180	70	250	360
SUMMER		100	100	130			300	140	150	180	150	170	100	200	90	100	120	100	160	160	240	230	170	180
FALL	240	300	310	260	210	200	230	220	280	240	200	170	150	120	130	130	150	190	190	290	140	150	290	310
WINTER	100	70	140	90	80	120	100	120	210	250	240	240	250	380	430	270	300	350	300	340	230	390	380	320

GREENWOOD SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING	140	140	180	130	130	80	100	110	110	130	100	100	80	90	70	100	120	110	280				70	80
SUMMER							90	180	180	200	270	220	150	150	150	170	310	260		50		240	200	
FALL	320	290	280	270	220	310	280	230	190	250	230	230	120	190	190	210	220	200	210	230	230	300	360	350
WINTER	330	330	300	210	270	300	260	250	310	280	230	270	310	250	230	320	520	570				620	760	370

Thermal internal boundary layers occur quite frequently in the lakeshore environment because of the different heat capacity between land and water. As the cooler air off the lake is warmed by the land, the air becomes convectively unstable and a TIBL forms over the land. The TIBL can be several hundred meters in depth depending upon ground heating. Since the air within a TIBL is very unstable, plumes emitted at the shoreline area would be mixed to ground by vertical eddies filling the TIBL and resulting in relatively high ground-level concentrations of pollutants. The formation of the TIBL has been studied intensively in the Nanticoke area (Lui, 1979; Kerman et al, 1982). In the present study, TIBL's were determined from the acoustic sounder data.

Table XII shows the seasonal frequency of occurrence, in percentage, of the TIBL for the three sites during onshore flow days in the 1982 study period. It can be seen that all TIBL's developed during the day time. The frequency of occurrence was higher and the duration of the TIBL persisted longer at the inland sites than at the lakeshore site. The average heights of the TIBL at the three sites by hour and season are given in Table XIII. The maximum height of the TIBL occurred in the fall and winter months.

3.1.5 Summary of the Results

The wind rose at the Lakeshore site indicates that onshore winds occurred approximately 35% of the time during spring, summer and fall and 29% in the winter, 1982. The predominant onshore wind speeds were in a range between 10 and 20 km h^{-1}.

During these onshore wind days, 80% of the time the atmosphere at the Lakeshore site was stable; 9.2% and 10.8% of the time it was unstable and neutral, respectively. The corresponding percentages of these three stability conditions at the Zoo site and Greenwood site were 61%, 24.1% and 14.9% and 63.1%, 28.3% and 8.6%, respectively. Thus, if an atmospheric release occurs at Pickering NGS, there is a high probability that the initial release takes place into a stable atmosphere.

Subsequently, the release would be well mixed within the mixed layer. The mixed layer is the region within which air pollutants are mixed by turbulence. It is called a TIBL if the turbulence is generated by thermal buoyancy. The mixed layer is usually capped by an inversion. Inversions are very stable. The acoustic sounder data show that both TIBL's and inversions occur frequently in the Pickering area.

During the formation of a TIBL, the low-level releases would be trapped within the mixed layer. Higher level releases (release at a level above the TIBL height) would be expected to travel initially in a stable layer until they intersect the TIBL at which time accelerated mixing would occur, leading to mixing throughout the TIBL.

TABLE XII

SEASONAL FREQUENCY OF OCCURRENCE (%) OF
THE THERMAL INTERNAL BOUNDARY LAYER IN 1982

LAKESHORE SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING										2	2	2	2											
SUMMER							2	2	5	3	3	2	2											
FALL									7	9	8	9	9	7	7	5	3	1						
WINTER									1	1	1													

ZOO SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING							1	4	5	5	5	5	5	5	5	5	5	4	3					
SUMMER								1	11	13	15	10	6	6	6	6	7	7	3					
FALL								2	10	20	24	23	19	17	17	16	13	2	1					
WINTER									4	9	10	9	8	8	8	8	8	4						

GREENWOOD SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING							2	7	11	11	10	10	7	8	8	8	10	10	2					
SUMMER							4	15	21	19	15	13	10	10	8	6	8	8	2					
FALL								3	13	29	27	22	18	18	16	16	10	3						
WINTER									3	7	7	7												

TABLE XIII

AVERAGE HEIGHTS (m) OF THE THERMAL INTERNAL BOUNDARY LAYER BY HOUR PER SEASON IN 1982

LAKESHORE SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING										40	45	60	40											
SUMMER							200	200	180	210	200	140	200											
FALL									110	240	210	160	150	320	320	310	290	280						
WINTER									40	140	220													

ZOO SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING							150	200	200	160	210	230	240	250	210	190	170	140	140					
SUMMER								80	100	180	240	250	250	190	170	160	160	120	60					
FALL								70	140	230	290	320	330	310	280	230	150	170	60					
WINTER									190	210	260	330	350	350	320	280	190	230						

GREENWOOD SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SPRING								220	210	210	210	280	210	240	250	210	180	110	180					
SUMMER							100	150	230	310	280	320	280	280	330	220	190	180	40					
FALL								160	210	210	300	390	400	400	340	260	230	300						
WINTER									140	200	280	370												

It is also possible for the releases to reach the ground in the downwash caused by the building wake effect, and produce high ground-level concentrations close to the power plant. However, the plume trapped within the wake would eventually be dispersed outside the wake boundary in puffs and then would behave as a continuous release from an area source.

3.2 Analytical Aspects

Previous studies (Hoff, et al, 1982; Tam, 1983) have shown that very high pollution concentrations can be expected at the ground when trapping or fumigation occur. Trapping occurs when pollutants are released inside the mixed layer, in other words, when an elevated inversion exists above the point of emission. Fumigation occurs when the pollutant plume interacts with the thermal internal boundary layer (TIBL) or the mixed layer. Thus, it is desirable to be able to predict the growth rate of the mixed layer.

The development of a TIBL has been studied by many previous investigators. Examples are Lyons and Cole (1973), Peters (1975), Venkatram (1977) and Misra (1980). As these studies indicate, the growth rate of a TIBL is largely dependent upon the surface heating.

This section attempts to discuss the surface heat flux at the Pickering area and provide an analytical model to predict the growth rate of a TIBL.

3.2.1 Surface Heat Fluxes

As summarized by Munn (1966) and Oke (1979), the contributions to the surface heat flux include short-wave radiation from the sun, long-wave radiation from the atmosphere and earth, the transfer of sensible heat through the air and ground, the contribution of latent heat of evaporation or condensation and anthropogenic heat.

For a closed system or over a long period of time, these heat fluxes should be balanced. Thus,

$$Q_R + Q_L + Q_A = Q_H + Q_E + Q_S \qquad (3\text{-}1)$$

where Q_R is the solar radiation, Q_L is the net long-wave radiation, Q_A is the anthropogenic heat flux, Q_H is the sensible heat flux, Q_E is the latent heat flux and Q_S is the heat flux through the soil layer, and values are averaged over a suitably long period of time.

In general, sensible heat is the primary heat flux component determining the growth of a TIBL. Sensible heat is the addition or subtraction of energy to a body due to the rise or fall in its temperature. By day, when the surface is heated, the sensible heat flux is directed upward to the atmosphere. At night, the surface is cooled and the sensible heat flux is directed downward from the atmosphere to ground. Thus, the temperature gradient is required to determine the intensity of the surface sensible heat flux. On the other hand, the surface sensible heat flux can also be determined by the above-mentioned energy balance equation (3-1).

Considering dry air conditions and neglecting the terms which involve the anthropogenic heat and soil heat fluxes (since the Pickering area is rural and soil heat flux is usually an order of magnitude less than the sensible heat flux), Equation (3-1) may be simplified to

$$Q_R + Q_L = Q_H \qquad (3\text{-}2)$$

The left-hand side of this equation represents the net incoming and outgoing radiation which is the output of the net pyrradiometer being used in the present study. Therefore, results from the net pyrradiometer may be useful to estimate the growth of the TIBL.

Table XIV shows the average net radiation observed at the Lakeshore site and the Zoo site for the months May to October in 1982. Generally, the amount of net radiation increases rapidly after sunrise and reaches the peak at noon. It then begins to decline. Radiative cooling (negative values in the table) is clearly shown in the early morning and at night.

3.2.2 Growth Rate of the Thermal Internal Boundary Layer

As discussed in previous sections, a TIBL develops when cool stable air over a lake surface moves onto the land and is warmed up by the underlying surface. Based on the fact that the height of a TIBL increases as the heat input increases, the growth rate of a TIBL may be predicted by an advection model.

The advection model that is described here is a modified form of the urban heat island model developed by Summers (1965). Let the temperature gradient over the land within the TIBL be Γ and the temperature gradient over the lake and above the TIBL be γ. The land-lake temperature contrast ΔT may then be given by

$$\Delta T = T_x - T_o = [\Gamma - \gamma]\, h_x \qquad (3\text{-}3)$$

where T_x is the temperature at the distance x inland from the shore, T_o is the temperature at the shoreline or the lake surface temperature and h_x is the height of the TIBL at the distance x inland from the lake.

It is also assumed that the wind velocity is constant in time and space, and that by the time the lake air has moved a distance x inland from the shore, the added heat is mixed vertically within the TIBL to give a uniform temperature. Then, the total amount of heat added to a small vertical air column of h_x in height and ΔA in area in unit time can be expressed as

$$H_t = \rho C_p \bar{U} \Delta A \int_o^{h_x} T_x \, dZ \qquad (3\text{-}4)$$

Here ρ is the air density, C_p is the specific heat of dry air at constant pressure and $\bar{U}$ is the mean wind velocity.

TABLE XIV

AVERAGE NET RADIATION (MJ m^{-2}) OBSERVED AT THE LAKESHORE AND ZOO SITE IN 1982

LAKESHORE SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
May	-.1	-.09	-.08	-.08	-.07	0	-.17	.46	.72	1.0	1.23	1.27	1.38	1.31	1.15	.85	.58	.29	.03	-.1	-.11	-.12	-.11	-.1
June	-.12	-.12	-.12	-.11	-.1	-.02	-.17	.44	.73	1.01	1.23	1.34	1.46	1.38	1.19	1.04	.68	.4	.11	-.09	-.13	-.13	-.13	-.13
July	-.15	-.14	-.14	-.14	-.13	-.07	-.16	.53	.96	1.29	1.57	1.77	1.85	1.62	1.45	1.24	.88	.5	.13	-.11	-.15	-.15	-.15	-.14
Aug	-.14	-.13	-.13	-.12	-.12	-.1	-.16	.44	.72	1.06	1.39	1.35	1.29	1.12	1.05	.83	.48	.21	-.04	-.14	-.15	0.15	-.15	-.14
Sept	-.12	-.12	-.11	-.11	-.12	-.12	-.03	.27	.5	.85	.95	.98	1.05	.95	.73	.42	.22	0	-.1	-.14	-.14	0.13	-.12	-.12
Oct	-.16	-.15	-.15	-.15	-.15	-.15	-.1	.09	.39	.76	.98	1.06	1.12	.99	.82	.47	.09	-.14	-.17	-.16	-.17	-.18	-.19	-.17

ZOO SITE

Time (EST)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
May	-.18	-.19	-.16	-.15	-.14	-.08	.18	.58	.94	1.23	1.5	1.67	1.77	1.46	1.3	.9	.69	.35	.03	-.16	-.18	-.19	-.19	-.18
June	-.12	-.1	-.11	-.1	-.08	0	.19	.46	.78	1.13	1.39	1.33	1.13	1.18	1.04	.98	.62	.33	.13	-.06	-.11	-.13	-.12	-.12
July	-.14	-.13	-.12	-.12	-.12	-.06	.16	.56	.92	1.25	1.4	1.66	1.7	1.59	1.33	1.16	.89	.45	.12	-.11	-.15	-.14	-.14	-.14
Aug	-.13	-.13	-.13	-.12	-.12	-.08	.09	.5	.77	1.15	1.54	1.45	1.35	1.3	1.21	.92	.61	.27	-.01	-.13	-.13	-.13	-.13	-.13
Sept	-.1	-.09	-.09	-.09	-.1	-.11	-.03	.24	.51	.71	.84	1.03	1.01	1.07	.82	.49	.25	.02	-.05	-.12	-.12	-.11	-.1	-.1
Oct	-.13	-.12	-.12	-.12	-.11	-.11	-.07	.1	.39	.63	.8	.87	.84	.76	.58	.34	.07	-.1	-.12	-.12	-.12	-.14	-.14	-.12

Similarly, the total heat added to this same air column at the shoreline is

$$H_o = \rho C_p \bar{U} \Delta A \int_o^{h_x} [\Gamma_o + (\Gamma-\gamma)Z] \, dZ \qquad (3\text{-}5)$$

Thus, the total heat gained by the air over the land is $(H_t - H_o)$. If there is no other heat source in addition to solar radiation in the study area, $(H_t - H_o)$ must be equal to the net solar radiation received at the surface in that unit time.

Let the net solar radiation be Q(x), then

$$H_t - H_o = \Delta A \int_o^x Q(x) \, dx \qquad (3\text{-}6)$$

Substituting (3-4) and (3-5) into (3-6) yields

$$h_x^2 = \frac{2}{\rho C_p \bar{U} (\Gamma-\gamma)} \int_o^x Q(x) \, dx \qquad (3\text{-}7)$$

Since the solar radiation is a large-scale meteorological variable, microscale effects become insignificant in determining its value. Thus

$$h_x^2 = \frac{2Q\,x}{\rho C_p \bar{U} (\Gamma-\gamma)} \qquad (3\text{-}8)$$

This is the general form for the height of the TIBL at a distance x inland from the shore in terms of the net solar radiation and surface meteorological factors. The larger net solar radiation is associated with a higher TIBL. Since the relationship between the surface heat flux and the growth rate of the TIBL is included, this model may be used for preliminary assessments of TIBL heights.

4.0 CASE STUDIES

The purpose of this section is to provide examples of the dispersion climatology which occurs in the Pickering area. Of the onshore flow days, August 16, 1982 and August 31, 1982 were selected for this study because of their relatively complete observational data set obtained from the present instrumentation package and the presence of conditions conducive to lake breeze formation. The likely behaviour of a plume resulting from a low-level (~50 m) release is also discussed for each case.

4.1 Case 1: August 16, 1982

Figure 6 displays the surface weather map at 1200 GMT for August 16, 1982. A low pressure system was centered over northern Quebec with a cold front extending southwestward through Lake Superior to the northwestern States. This cold front had no effect on the local weather over southern Ontario until the next day when it passed. There were two high pressure systems on this day, the northern one centered over the prairie Provinces and the southern one situated just off the New Jersey coast. The air flow was generally light since the surface pressure gradients over Lake Ontario were quite slack on this day.

The surface winds observed at the Lakeshore site and the Greenwood site are given in Table XV. The prevailing winds at these two sites were northerly in the morning hours, southerly during the day time and northerly again at night. The wind speeds were generally stronger at the Lakeshore site than at the Greenwood site which typically reflects a lake breeze case.

Onshore (southerly) flow was observed at the Lakeshore site from 0800 EST to 1900 EST. The average onshore wind speed was 8.0 km h^{-1}, which is slightly stronger than the average wind speed of 7.5 km h^{-1}. At the Greenwood site, onshore flow was first observed at 1100 EST and persisted to 1800 EST with an average wind speed of 6.5 km h^{-1}. The average wind speed for the other hours was 2.0 km h^{-1}.

Lake breezes develop mainly as a result of the temperature contrast between land and lake. The high surface temperature over the land enhances an upward motion due to buoyancy. The upward motion causes a low pressure center at the land surface. Consequently, an onshore flow is generated by the horizontal pressure gradient. Figure 7 displays the surface temperature observed at the Lakeshore site and the Zoo site. A diurnal variation of surface temperature is clearly depicted in this figure. The maximum diurnal temperature differentials at these two sites were 8°C and 15°C, respectively. The lake surface temperature was not available on this day. However, Munn et al (1969) have pointed out that in summer, shoreline temperatures at Toronto (north shore of Lake Ontario) averaged 2° to 4°C less than points inland during periods of onshore flow. Besides, water exhibits less diurnal change in temperature than do land surfaces due to its high heat capacity.

Therefore, an elevated advection inversion may be developed in the lower levels of the atmosphere when the air over the lake moves over a relatively warm land surface. This can be seen from the acoustic sounder signals as shown in Figure 8. Complex layer echoes were observed in the early morning hours close to the ground. This layer is called the "nocturnal stable layer" which is caused by radiative cooling overnight. The depths of this nocturnal stable layer were about 200 m at the inland site and 150 m at the Lakeshore site.

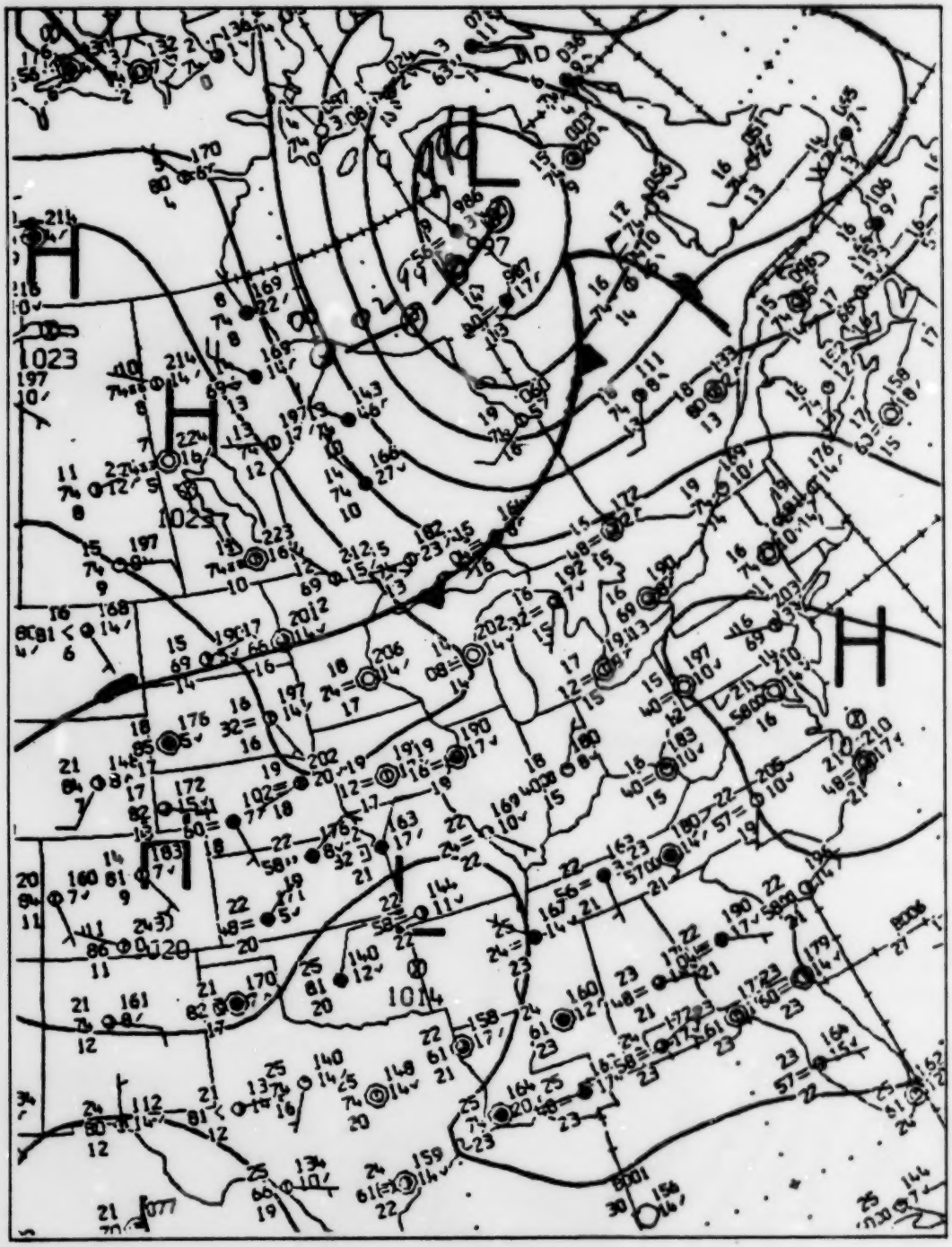


FIGURE 6

SURFACE WEATHER MAP AT 1200 GMT FOR AUGUST 16, 1982

TABLE XV

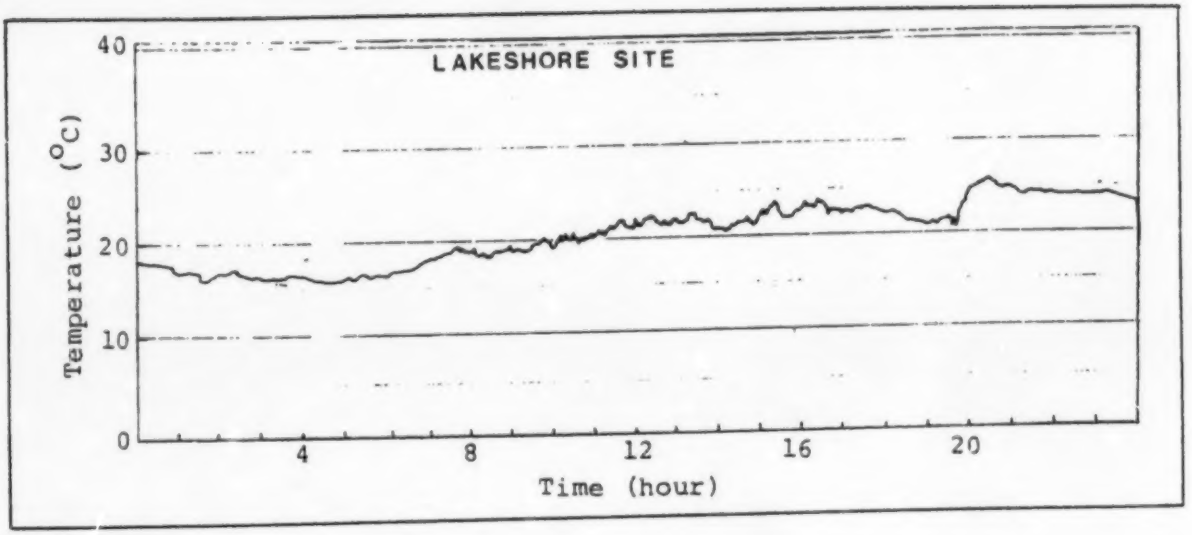
SURFACE WINDS OBSERVED AT THE LAKESHORE AND GREENWOOD SITES ON AUGUST 16, 1982

LAKESHORE SITE

Time (EST)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Speed (Km/h)	5	5	5	7	8	6	7	5	7	9	7	9	9	8	8	7	6	9	14	9	11	10	11	8
Direction (from)	N	N	W	NW	N	N	NNW	SSW	SSW	SSW	S	SW	SW	SW	S	SSW	SW	SW	WSW	WWW	WWW	WWW	W	W

GREENWOOD SITE

Time (EST)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Speed (Km/h)	3	0	2	0	2	2	2	0	0	3	5	6	8	10	8	8	4	3	2	4	4	3	4	3
Direction (from)	N	N	NW	N	N	N	N	NW	W	NNW	S	S	S	S	S	S	S	SW	W	NW	WNW	WSW	W	W



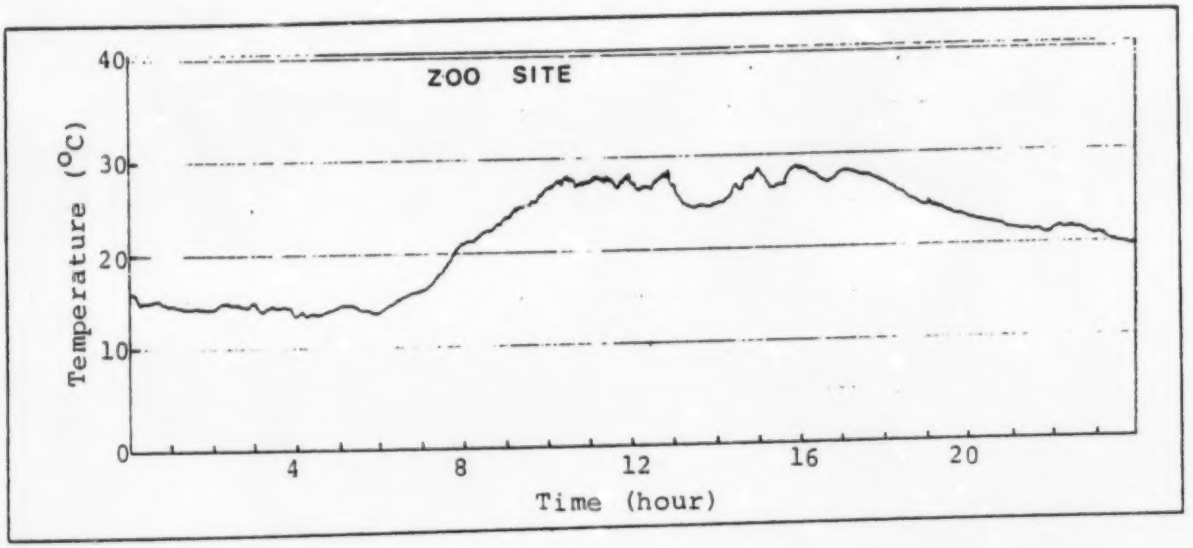


FIGURE 7

SURFACE TEMPERATURES OBSERVED AT THE
LAKESHORE AND ZOO SITES ON AUGUST 16, 1982

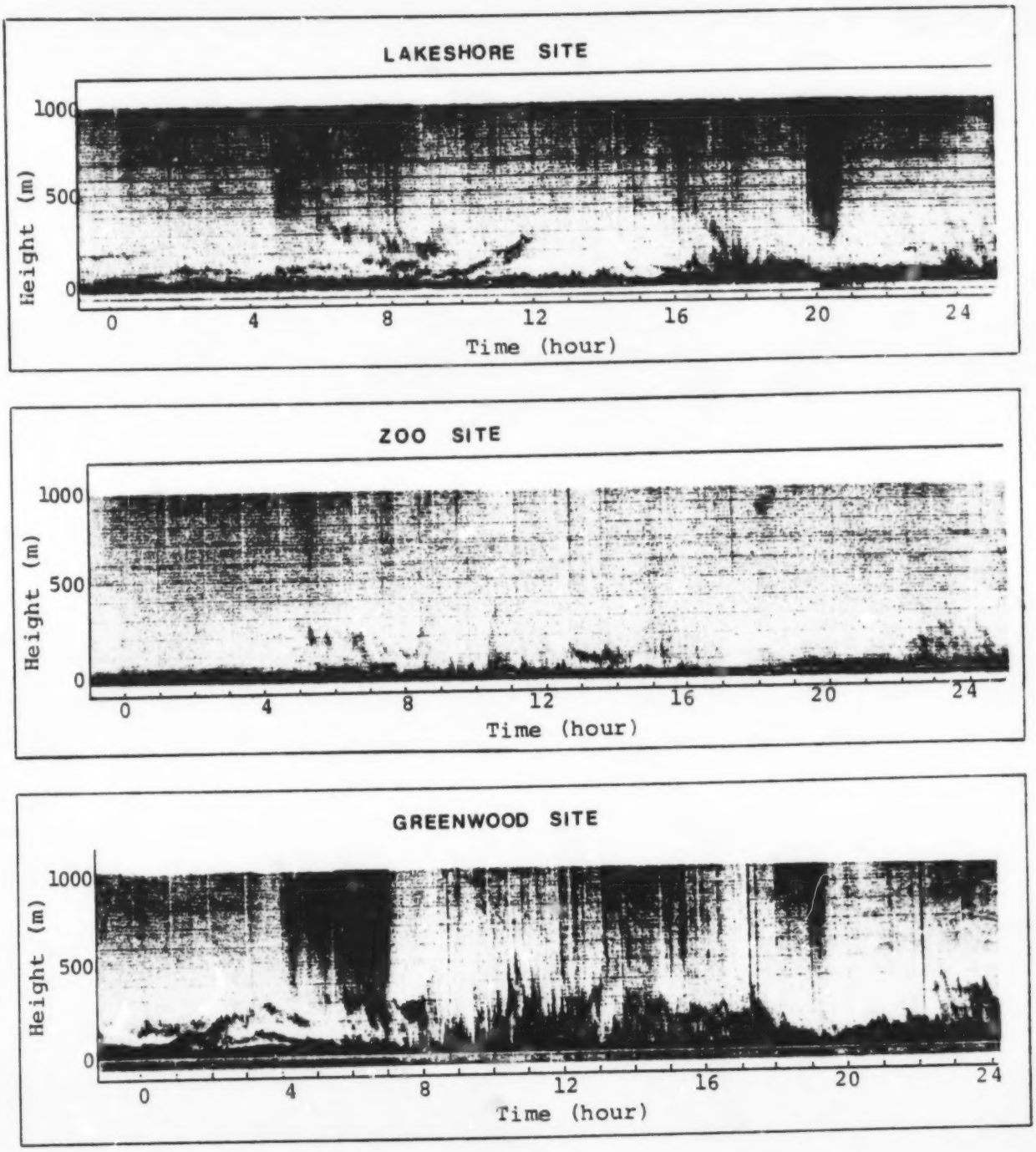


FIGURE 8

ACOUSTIC SOUNDER SIGNALS OBSERVED ON AUGUST 16, 1982

This stable layer was forced to rise by surface convective activities after sunrise at about 0600 EST and became an elevated inversion. This is confirmed by Figure 8 since spike echoes or unstable conditions were observed below the inversion.

During most of the day, the sounder at the Lakeshore site showed short spiky signals which may be identified as weak thermal activities. On the other hand, spike echoes were greatly intensified at the inland sites indicating strong thermal convections. As the day persisted and solar radiation increased, the elevated inversion at the inland sites gradually dissipated and the surface mixed layer extended to about 300 m and 500 m at noon at the Zoo site and the Greenwood site, respectively.

The net radiation observed at the Lakeshore and Zoo sites is displayed in Figure 9. Radiative cooling at night and warming during the day are shown in this figure (ordinate value of 20 represents zero solar radiation).

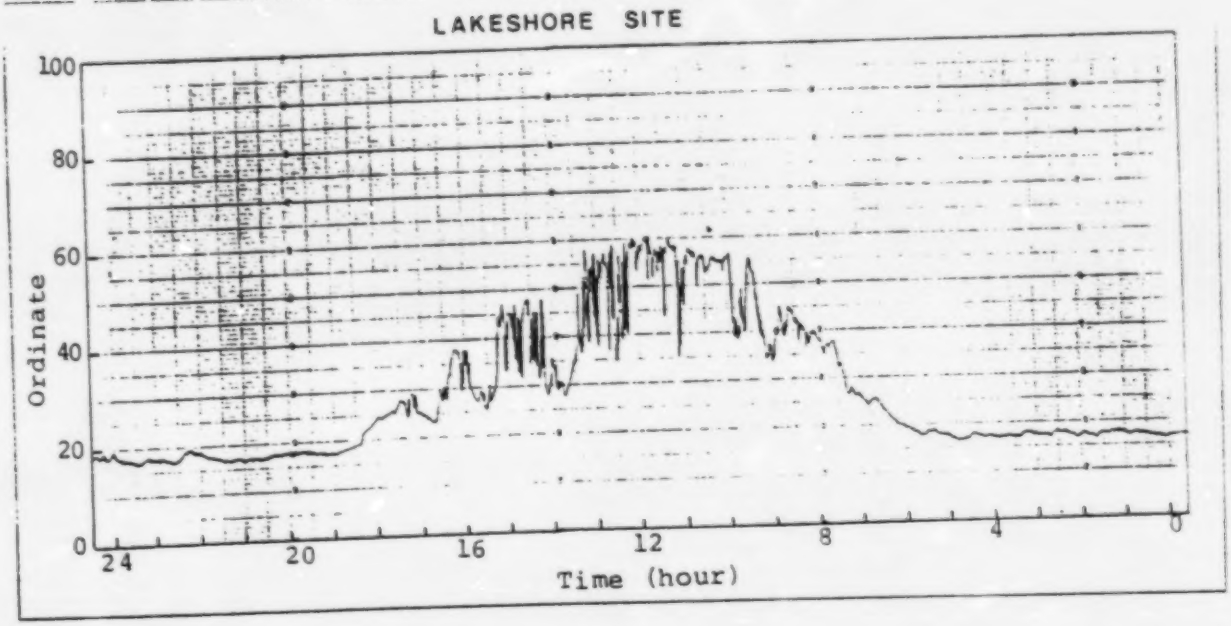
Table XVI presents TIBL heights calculated by the net radiation and wind data observed on August 16, 1982. The TIBL heights increase with distance inland and with increases in solar radiation.

TABLE XVI

TIBL HEIGHTS WITH DISTANCE INLAND FROM THE SHORE FOR VARIOUS HOURS ON AUGUST 16, 1982

Distance Inland (km)	Time (EST) 0800	1000	1200	1400	1600
1	53	71	77	54	45
2	75	101	109	77	63
3	91	123	133	94	77
4	105	142	154	108	89
5	118	159	172	121	100
6	129	174	188	133	109
7	139	188	203	143	118
8	149	201	218	153	126
9	158	213	231	162	134
10	167	225	243	171	141

Based on the above description of the atmospheric conditions and assuming a low-level (~50 m) release, a plume would be expected to exhibit the following behaviour.



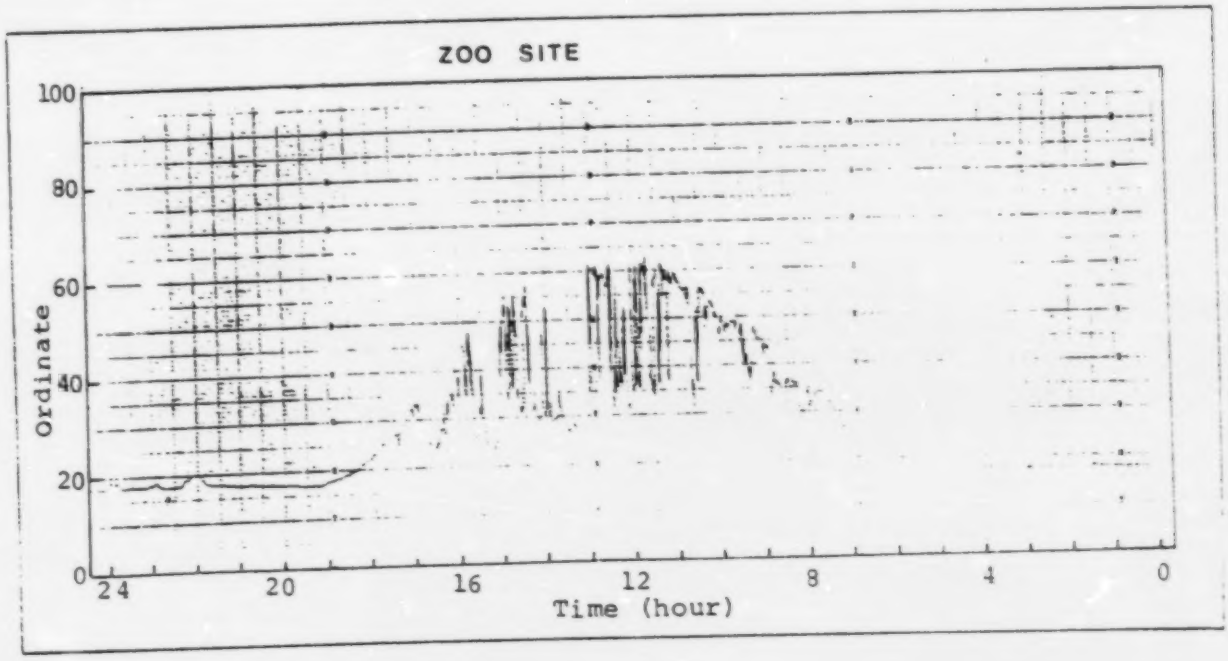


FIGURE 9

NET RADIATION OBSERVED AT THE LAKESHORE AND ZOO SITES ON AUGUST 16, 1982

Emissions would be released into a shoreline atmosphere with weak turbulent eddies in a shallow surface-based layer. The upward mixing of this plume would be prohibited by the overlying stable layer, the base of the stable layer being about 150 m above the ground at the Pickering shoreline. Except for nearly calm conditions, emissions would be entrained into the cavity which develops in the leeward side of the building by the building wake effect. Good mixing would be assured very close to the power plant, creating a 'plume' of cross-wind dimensions comparable to the projected area of the power plant.

Since the mixed layer below the inversion near the shoreline was slightly unstable, the plume would initially travel downwind as a cohesive plume with little lateral and vertical spread. However, the plume would experience dilution after travelling a distance inland where the deepening turbulent mixed layer (TIBL) had occurred due to strong surface thermal activities and overtaken the top of the plume. The calculated height of this mixed layer increased with distance inland. The maximum heights occurred at 1200 EST, in agreement with acoustic sounder data.
As seen from the data, the temporal variations of both wind speed and wind direction were small on this day. Thus, the rate of dilution would also be small. The ground-level concentrations of pollutants would be higher at the Greenwood site than at the Zoo site because the former was directly downwind of the source in this case.

Note that a full description of the behaviour of emissions should also include physical and chemical transformation and removal of pollutants by processes such as deposition or gravitational settling. These processes are also dependent on the state of the atmosphere. Observational and numerical modelling studies would be necessary for detailed investigations of these processes.

4.2 Case 2: August 31, 1982

The surface weather map for August 31, 1982 at 1200 GMT is displayed in Figure 10. There was a weak cold front situated to the south of the lower Great Lakes. The weather over Ontario was influenced by a high pressure system centered over the Kapuskasing area. Apparently, this high pressure system covered eastern North America; thus, the synoptic-scale air flow over Lake Ontario was northerly. The low centered over South Dakota at this time had no effect on the local weather of southern Ontario.

The surface winds observed at the Lakeshore and Greenwood sites on this day are listed in Table XVII. Northerly winds were predominant and consistent with the synoptic weather pattern. However, further examination of the wind data reveals that southerly flows developed during the day time. The southerly flow was observed from 1000 EST to 1700 EST at the Lakeshore site and from 1300 EST to 1900 EST at the Greenwood site. Even though the diurnal variation of surface temperature on this day was not as obvious as that on August 16, 1982, it still shows temperature differentials of about 3°C and 8°C at the Lakeshore and Zoo sites, respectively as shown in Figure 11.

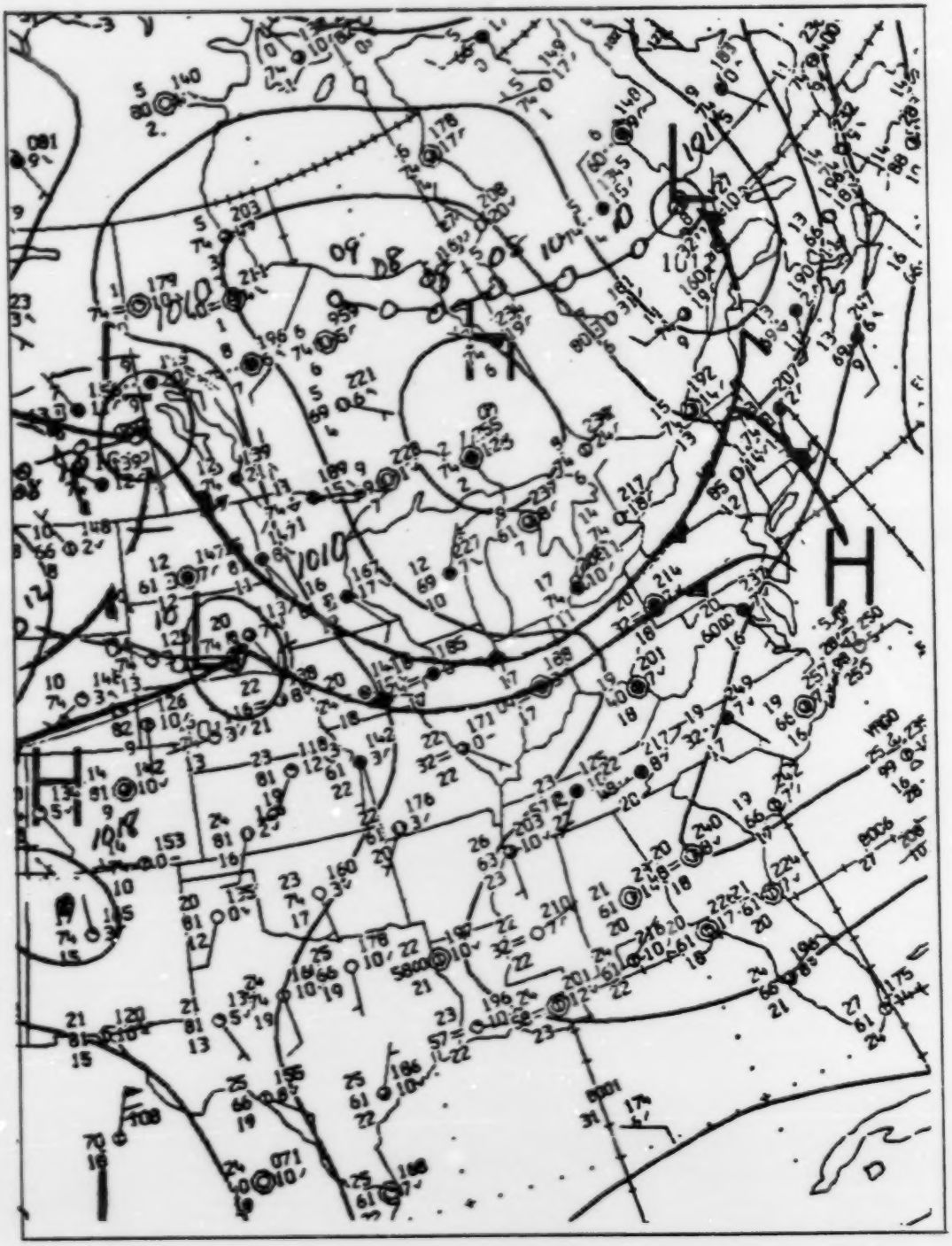


FIGURE 10

SURFACE WEATHER MAP AT 1200 GMT FOR AUGUST 31, 1982

TABLE XVII

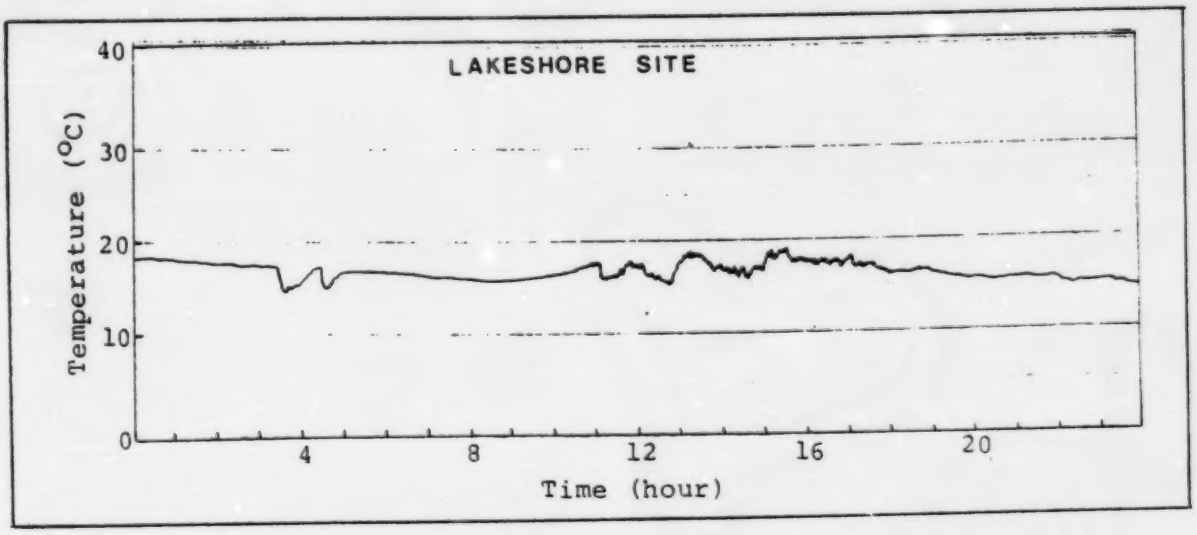
SURFACE WINDS OBSERVED AT THE LAKESHORE AND GREENWOOD SITES ON AUGUST 31, 1982

LAKESHORE SITE

Time (EST)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Speed (Km/h)	9	6	8	7	10	9	11	9	9	7	9	11	9	7	7	7	7	6	6	6	8	9	10	9
Direction (from)	NNW	NNW	WNW	NW	N	NNW	N	N	NNE	SE	S	SSE	SSE	ESE	SE	SE	SE	E	E	NE	NNE	N	N	NNE

GREENWOOD SITE

Time (EST)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Speed (Km/h)	3	3	1	0	2	3	3	0	2	4	4	4	7	7	5	6	4	3	0	3	2	2	2	0
Direction (from)	N	N	WSW	NW	NNW	NNN	NNW	N	ENE	NE	ENE	E	SE	SSE	SE	SSE	SE	S	S	NNE	NE	N	NNE	N



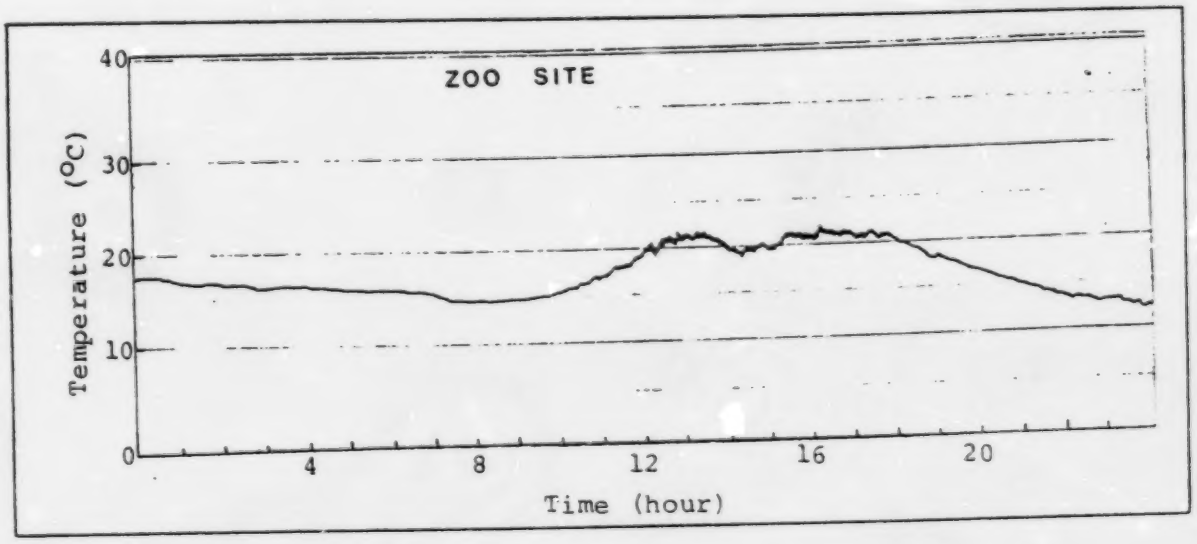


FIGURE 11

SURFACE TEMPERATURES OBSERVED AT THE
LAKESHORE AND ZOO SITES ON AUGUST 31, 1982

The maximum surface temperature was observed at 1300 EST at both sites on this day. The maximum surface temperature contrast between land and lake would also occur approximately at this hour. This would promote the development of a lake breeze.

The acoustic sounder signals and net radiation data observed on this day are displayed in Figures 12 and 13, respectively. Nocturnal stable layers (due to radiative cooling) were observed in the early morning hours at both inland sites. The depth of these stable layers was about 300 m. A multiple layer pattern which is associated with wind shifts was observed in the late morning hours. The passage of the lake breeze front was also noted from the acoustic sounder signals as very large amplitude buoyancy waves appearing at around 1300 EST.

There were no acoustic sounder data available at the Lakeshore site on this day. However, in view of those observed at the two inland sites, it may be assumed that the thermal structure of the lower atmosphere at the shoreline area was also very complex.

The TIBL heights calculated by the net radiation and wind data on this day are given in Table XVIII. Again, the TIBL heights increase with distance inland; but the maximum heights occurred at 1400 EST on this day.

TABLE XVIII

TIBL HEIGHTS WITH DISTANCE INLAND FROM THE SHORE FOR VARIOUS HOURS ON AUGUST 31, 1982

Distance Inland (km)	Time (EST)			
	1000	1200	1400	1600
1	64	70	72	52
2	91	99	102	73
3	112	122	125	90
4	129	140	144	104
5	144	157	161	116
6	158	172	177	127
7	171	186	191	137
8	182	198	204	146
9	193	210	216	155
10	204	222	228	164

Based on this atmospheric condition, the following emission behaviour for a low-level (~50 m) release would be expected during the onshore flow period that occurred on August 31, 1982.

After release, the pollutants will travel with the surface winds. As seen from Table XVII, the surface winds at the Lakeshore site were backing from the southeast to the east. This perpetual variation of wind direction would lead to plume stretching.

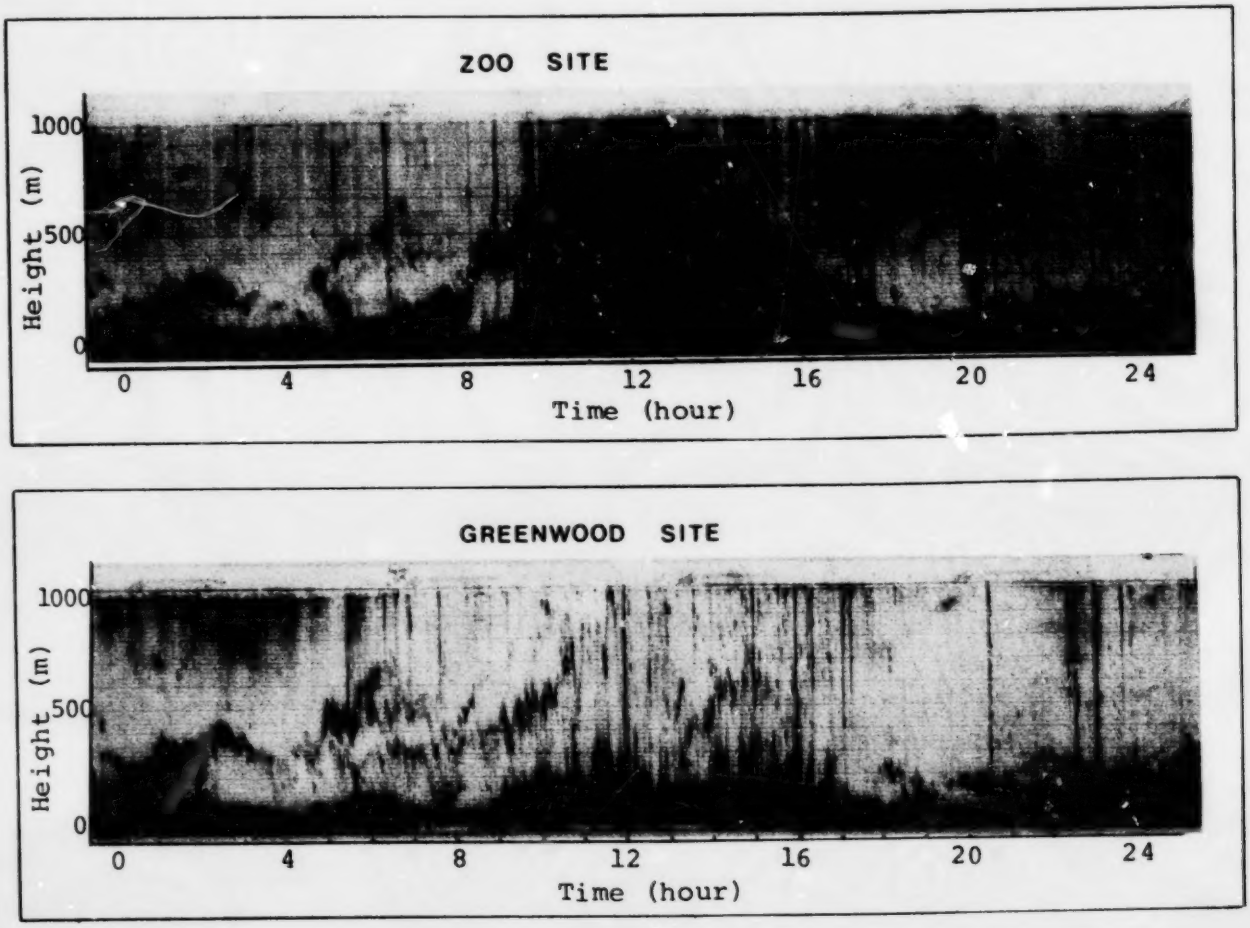
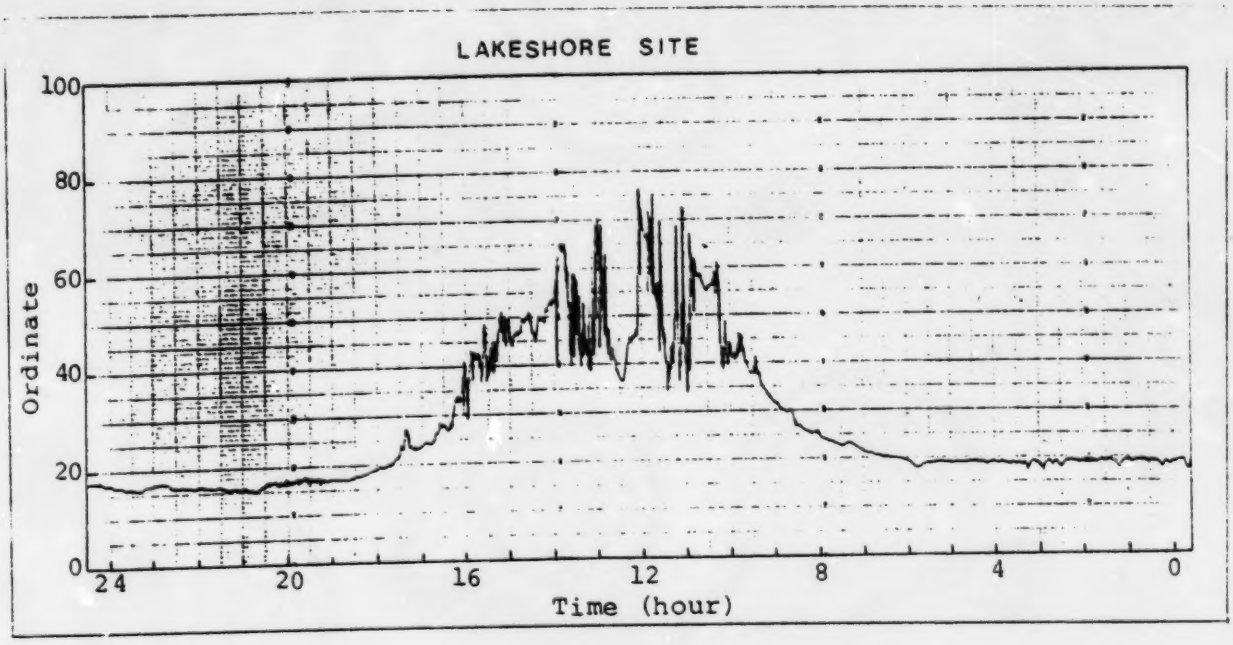


FIGURE 12

ACOUSTIC SOUNDER SIGNALS OBSERVED ON AUGUST 31, 1982



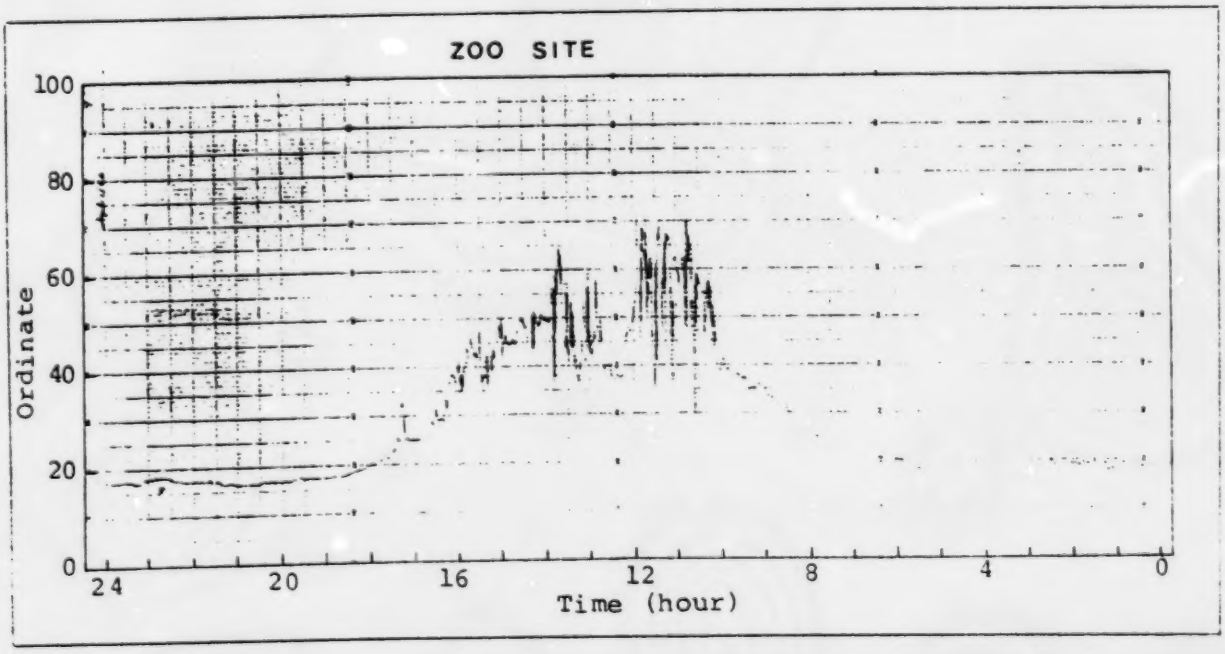


FIGURE 13

NET RADIATION OBSERVED AT THE LAKESHORE AND ZOO SITES ON AUGUST 31, 1982

The outline of the plume would then cover a wider area than for the case of a constant wind direction such as Case 1, discussed earlier. The wind direction variation would also affect the rate of plume dilution and horizontal plume spread.

The vertical dispersion of pollutants is controlled by the atmospheric stability and the depth of the surface mixed layer. Acoustic sounder data (Figure 12) reveal that the atmosphere was unstable during the onshore flow period and the unstable layer extended to a height of about 500 m. Thus, looping would be expected to occur. Subsequently, instantaneous high ground-level concentrations would be observed around the region northwest of Pickering NGS. Since looping involves a high degree of both vertical and horizontal turbulence, its development would be very complicated and has not yet been adequately predicted.

Building wake effects are expected to play a comparable role in this case. Further research effort is needed to determine its significance.

5.0 CONCLUDING REMARKS

The dispersion climatology of the Pickering area was studied by a year-long experimental program in 1982. The instrumentation used in the program included three acoustic sounders, two net pyrradiometers, two anemometers and two thermocouples. This instrument package was operated at three sites in the vicinity of Pickering NGS. These three sites were positioned in a triangular configuration with one lakeshore site very close to Pickering NGS and two inland sites located separately at the Metro Zoo and the Greenwood Conservation Area.

The acoustic sounders provided information on the thermal structure of the atmosphere. The net pyrradiometers provided net solar radiation at the surface. The anemometers and thermocouples measured the surface wind velocity and temperature, respectively.

The surface wind velocity, atmospheric stability, and height of the mixed layer are the most important meteorological variables determining dispersion and transport of air pollutants. Data collected by the above-mentioned instrument package were analyzed to determine the seasonal and diurnal frequency of occurrence of these meteorological variables for onshore flow conditions.

During onshore flow days, it was found that the atmosphere at the Lakeshore site exhibited stability 80% of the time, whereas at the Zoo and Greenwood sites, the figures were 61% and 63%, respectively. The frequency of occurrence of unstable conditions was higher at the inland sites than at the lakeshore site.

Generally, a plume is most rapidly dispersed when there is a great deal of turbulence or mixing in the atmosphere. An inversion usually exists above the surface mixed layer. In the Pickering area, nocturnal inversions occurred frequently during onshore flow days, especially in the early morning or late evening hours. During the day time,

the surface-based inversions were lifted to higher levels as the result of thermal convection caused by heating of the surface. Since the diurnal variations of temperature in land surfaces are larger than those in water surfaces, the depths of mixed layers are greater at the inland sites than at the lakeshore sites. The highest frequency of occurrence of these elevated inversions in the Pickering area was found in the fall months.

As well, the fall months also accounted for the highest occurrence of the thermal internal boundary layer. Again, the TIBL heights were larger at the inland sites than at the lakeshore site.

Because of the configuration of the reactor buildings of Pickering NGS, building wake effects are considered to be significant. The low-level releases are expected to be trapped within the wake cavity on the leeward side of the reactor buildings. In light wind conditions, some emissions may disperse outside the wake boundary to a relative stable atmosphere while others may be mixed evenly down to the ground, a phenomenon known as downwash. The downwash would be much intensified when the wind speed is high. The dispersion characteristics are expected to be more complex in conjunction with the development of lake-breezes and TIBL's in the area.

An advection model was developed whereby the type of data collected in this study may be used to predict the growth rate of thermal internal boundary layers. The growth of a TIBL is highly dependent upon the surface sensible heat flux. Under dry conditions and according to a simple scale analysis for the Pickering area, it was demonstrated that the needed surface sensible heat flux could be measured by the net pyrradiometer. However, the model itself is flawed in that it assumed a uniform wind field within the TIBL. Further development is necessary to tune the model for operational prediction of TIBL growth.

Two episodes were discussed in terms of the local meteorological conditions and likely behaviour of emissions. Results indicate that continuous shoreline fumigation and trapping may occur over the Pickering area as emissions interact with the developing thermal internal boundary layer. Looping may also be comparably important for a low-level release in this area. Unfortunately, no concentration measurements were available to verify the predicted emission behaviour. A tracer study would be desirable to provide this information.

In conclusion, this report presents a preliminary study of the dispersion climatology at the Pickering area based on comprehensive meteorological data. This report also demonstrates the usefulness of remote sensing instruments, particularly acoustic sounders, to continuously assess site meteorological conditions. The acoustic sounder could provide the following meteorological information which is important to pollutant dispersion:

(1) Atmospheric stability at levels up to about 1 km in height.

(2) Height and thickness of inversions.

(3) Height, growth, complexity of inversion layers and intensity of turbulence within the planetary boundary layer.

(4) Vertical extent and horizontal dimensions of surface thermal eddies.

(5) Height and amplitude of wind shear waves.

(6) Discontinuities of air mass, such as frontal passages.

Some possible extension of this work to deal with limitations of the present study is discussed in the following.

The transport and dilution of pollutants depend on the winds. Unfortunately, winds vary not only horizontally from place to place and time to time, but also with height, especially near the ground. In the present study, the surface winds were measured at a height of 10 m above the ground. Winds at this height may be used to represent the general winds in the lowest 100 m of the atmosphere over a homogeneous and flat terrain. Obviously, they are not suitable for accurate calculations of pollutant dispersion over a shoreline environment where physical features are complicated.

Tam and Kerry (1983) have evaluated the operational usefulness of a Doppler acoustic sounder system and concluded that the Doppler system is capable of providing wind velocity profiles in addition to the thermal structures of the atmosphere. The measurements are given continuously and economically. Thus, the use of Doppler acoustic sounders is recommended for the future to obtain atmospheric thermal structure and wind velocities in the Pickering area.

Another factor that influences the pollutant dispersion is topography; mountains can restrict horizontal spreading and valleys may trap pollutants in a region between the valley walls. The main physical features of the Pickering area are a water body (Lake Ontario) and river ravines. The terrain height increases gradually inland from the lake. All these are of a microscale nature and their influence on pollutant dispersion needs further research, probably in the form of numerical modelling as suggested by Tam and Ogram (1983).

Finally, the chemical transformation of pollutants has not been discussed in this report. Chemical transformations depend highly on the species released and thus, to fully understand the transformation process, one must work closely with the chemistry of atmospheric pollutants. This is beyond the scope of the present study.

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